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Tactical decisions of concentrate level, slaughter age and carcass weight of bulls of five beef breeds under Norwegian conditions

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Beef production based on suckler cow breeds is a relatively new production system in Norway as in most Nordic countries. To ensure the continuation of this production, profitable management practices designed for Norwegian conditions have to be established. Thus a simulation model was developed that integrates the daily feed intake, the daily live weight (LW) gain, silage net energy concentration for beef production (feed units beef (FUb) kg$^{-1}$ dry matter) and price, concentrate level and price, and carcass price for bulls of the country’s five most common beef breeds. In this work the model was combined with production statistics to find general recommendations in the finishing of beef bulls under Norwegian conditions. Among all the five breeds the Limousin bulls had the highest estimated mean daily return and the Hereford bulls the lowest estimated mean daily return from 20 g concentrate kg$^{-1}$ LW$^{0.75}$ for the 940 FUb kg$^{-1}$ silage dry matter, and from 40 g concentrate kg$^{-1}$ LW$^{0.75}$ for the 800 FUb kg$^{-1}$ silage dry matter. Our estimated optimal slaughter ages and carcass weights shows that it pays to more intensively feed during the finishing period for all five breeds. Current farming practice in Norway for the five major breeds studied is that slaughter age is at least two months later with lighter carcass weights than the results expected from following our model estimated recommendations.

Key-words: feeding, silage intake, daily live weight gain, mean daily return, simulation model
Introduction

Beef production in Norway has traditionally been a sideline of the dairy industry, and cull cows and beef production from young dairy bulls still represents the major beef sources. However, the rapid decline of the dairy herd with the improvement of the milk cow’s productivity has lead to an increase in the number of suckler cows. The number of dairy cows has been reduced from 322,350 in 1997 to 258,720 in 2007 and during the same time the number of beef suckler cows increased from 26,490 to 56,360 (Statistics Norway 2008). According to the Norwegian Beef Cattle Recording System (Animalia 2008) crossbreeds make up 45% of the total number of beef cows while Angus (10%), Charolais (11%), Hereford (15%), Limousin (5%), and Simmental (4%) are the most common of the pure breeds. A typical suckler cow farm in Norway is a combined cow-calf enterprise and a bull finishing, or fattening, enterprise, and the prevailing beef finishing production system can be characterized as a grass silage system (Deblitz et al. 2008). The bull finishing enterprise will involve a number of inter-dependent decisions about the desired carcass weight, the slaughter age and silage to concentrate ratios and levels. Due to the large variation in weather conditions between sites and years (Skjelvåg 1998), the energy concentration (feed units kg⁻¹ dry matter) of the grass silage, and its price, will be variable which in turn will impact on the key decisions mentioned above. Given the yearly variation in silage price and quality, decisions regarding carcass weight, slaughter age and silage to concentrate ratios and levels can be regarded as tactical as they are the decisions that are necessary in order to make the whole farm strategy work over the duration of a production season (Sørensen and Kristensen 1989).

Decision support simulation models have been developed for beef finishing in other production systems, e.g. Williams and Bennet (1995) for steers in feed lot, Kilpatrick and Steen (1999) for a wide range of breeds of steers but only Charolais bulls, Nielsen and Kristensen (2007) for steers. The availability and use of such a tool developed for the bull finishing of a grass silage production system might contribute to better feeding and management practices in the beef finishing industry in Norway. Similar approaches are also applicable to other parts of Europe with bull finishing based on silage production systems, e.g. Austria, Germany, Poland and Sweden (Deblitz et al. 2008). Thus, in order to assist the farmers to make better tactical decisions in their finishing of bulls, a simulation model that integrates the feed intake, the daily LW gain, grass silage quality and price, concentrate level and price, and carcass price was developed by the feed industry and the Norwegian Agricultural Economics Research Institute. The objective of the current work was to combine this model with production statistics, i.e. average or typical numbers, from the Norwegian beef cattle recording system with other key factors to provide a tactical feeding recipe to maximize the return per head of finishing of the five most common pure beef breed bulls in Norway. Other factors incorporated include governmental payments and the seasonal variation of the beef price.

Material and methods

Database

The database for the development of the model was:

1. The INRA feeding tables of beef bulls (Garcia et al. 2007), based on a net energy system of feed units beef (FUb) used during many years in beef production in France. The INRA tables have separate tables for bulls of Charolais and Limousin. We assumed the table of “early maturing beef cattle” to correspond to bulls of Angus and Hereford. The feeding table for Charolais was also used for Simmental bulls.

and 2006–2007, for twelve bulls per year of each of the five breeds during 21 weeks. The overall years range of start and end weights for the bulls were from 230 kg to 645 kg for Angus, from 334 kg to 746 kg for Charolais, form 286 kg to 650 kg for Hereford, from 286 kg to 650 kg for Limousin, and from 332 kg to 760 kg for Simmental. At the test station the bulls were fed on a typical Norwegian grass silage, consisting of mainly timothy (Phleum pratense) and meadow fescue (Festuca pratensis), and concentrate pellets (1090 FUb kg⁻¹ dry matter) (Table 1).

3. EUROP- conformation, fatness, and weaning weights for bulls of the five breeds from The Norwegian Beef Cattle Recording System from 2001 to 2007 (e.g. Animalia 2008). Altogether 40% of the total beef cattle population in Norway is included in the recording system, and the total number of bulls recorded during the years 2001 to 2007 were 94 661 head.

### Model description

The model is for Angus, Charolais, Hereford, Limousin, and Simmental beef bulls finishing within the range of weights as given in the INRA tables (Garcia et al. 2007). The model is based on the state and rate approach (Goudriaan and van Laar 1994). The time interval of the model is one day. The model reflects the dynamics in the daily

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**Table 1. Characteristics of the feed rations for bulls of five beef breeds at the Norwegian beef breeders test station:** The silage energy concentration in feed unit beef (FUb) per kg dry matter (DM), the silage dry matter concentration, and the mean and range of the daily concentrate ratio. The silage was stored in two pits, silage pit 1 (S1) and silage pit 2 (S2), the time in weeks the bulls were fed from a silage pit is given in brackets.

<table>
<thead>
<tr>
<th>Year</th>
<th>Breed</th>
<th>Silage, g FUb kg⁻¹ DMᵃ (time, weeks)</th>
<th>Silage DM concentration, g DM kg⁻¹</th>
<th>Concentrate, kg day⁻¹</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006–2007</td>
<td>Angus</td>
<td>1017 (20) 939 (2)</td>
<td>522 296</td>
<td>3.9 [3.6−4.0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charolais</td>
<td>1017 (22) 939 (2)</td>
<td>522 296</td>
<td>5.1 [3.9−6.0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hereford</td>
<td>1017 (20) 939 (2)</td>
<td>522 296</td>
<td>3.9 [3.7−4.0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limousin</td>
<td>1017 (22) 939 (2)</td>
<td>522 296</td>
<td>5.2 [3.8−5.8]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simmental</td>
<td>1017 (22) 939 (2)</td>
<td>522 296</td>
<td>5.0 [3.9−6.1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005–2006</td>
<td>Angus</td>
<td>874 (18) 770 (4)</td>
<td>219 240</td>
<td>4.6 [3.7−4.8]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charolais</td>
<td>874 (20) 770 (2)</td>
<td>219 240</td>
<td>5.2 [4.0−5.5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hereford</td>
<td>874 (19) 770 (3)</td>
<td>219 240</td>
<td>4.6 [3.7−4.8]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limousin</td>
<td>874 (20) 770 (2)</td>
<td>219 240</td>
<td>5.4 [4.0−5.6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simmental</td>
<td>874 (20) 770 (2)</td>
<td>219 240</td>
<td>6.6 [5.0−7.2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charolais</td>
<td>952 (9) 978 (13)</td>
<td>321 367</td>
<td>4.8 [4.0−5.2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hereford</td>
<td>952 (10) 978 (12)</td>
<td>321 367</td>
<td>4.4 [3.6−4.6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limousin</td>
<td>952 (9) 978 (13)</td>
<td>321 367</td>
<td>4.8 [4.0−5.3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simmental</td>
<td>952 (9) 978 (13)</td>
<td>321 367</td>
<td>5.1 [4.0−5.5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003–2004</td>
<td>Angus</td>
<td>887 (22) 263</td>
<td>423 263</td>
<td>4.2 [3.7−4.7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charolais</td>
<td>887 (22) 263</td>
<td>423 263</td>
<td>4.7 [4.0−5.7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hereford</td>
<td>887 (22) 263</td>
<td>423 263</td>
<td>4.1 [3.7−4.6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limousin</td>
<td>887 (22) 263</td>
<td>423 263</td>
<td>4.9 [3.6−5.4]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simmental</td>
<td>887 (22) 263</td>
<td>423 263</td>
<td>4.8 [4.0−5.7]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ᵃ The silage energy concentration is determined by the use of Near Infrared Spectroscopy (NIRS), 1000 FUb = 6.9 MJ net energy beef.
silage and concentrate energy intake and the daily live weight gain, and the model also simulates the dressing percentage, the EUROP conformation and the fatness score on a daily basis (Table 2).

The silage intake model was based on the approach of dry matter (DM) intake capacity related to $LW^{0.75}$ of bulls and the energy concentration of the silage ($FUb_{conc} = 0.001 \times FUb \text{ kg}^{-1} \text{ Silage DM}$) of different types of grasses (Baumont et al. 1999), combined with the effect of concentrate - grass silage substitution (McNamee et al. 2001). This combined approach offers a very simple description of the key factors that influence the silage intake.

The potential intake capacity of DM ($SDMI_{pot}$) of the silage of timothy and meadow fescue was assumed to lie between the silage of orchard grass ($Dactylus glomerata$) and perennial ryegrass ($Lolium perenne$) as given by Baumont et al. (1999) and was, by using the Proc Model routine of SAS (SAS Institute Inc 1999a), quantified to:

$$SDMI_{pot} (g \text{ kg}^{-1} \text{ LW}^{0.75} \text{ d}^{-1}) = (0.07730 - 0.07538 \times FUb_{conc} + 0.07388 \times FUb_{conc}^2) \times LW_{t-1}^{0.75}$$

where $LW_{t-1}$ is the LW the day before.

The reduction index in silage DM intake related to the level of concentrate in the feed ration, $f(CI)$, was estimated according to McNamee et al. (2001):

$$f(CI) \text{ (dimensionless)} = 1 - 0.001888 \times CI - 0.0001102 \times CI^2$$

The daily actual silage DM intake ($SDMI_{act}$) was then obtained by the product of $SDMI_{pot}$ and $f(CI)$. The combination of the $SDMI_{pot}$ (Equation 1) and the reduction index (Equation 2) implies a lower absolute reduction in silage intake (kg DM day$^{-1}$) for silage of a lower energy concentration, than for silage with a higher energy concentration if the bulls receive the same concentrate ration (kg d$^{-1}$). Differences among the five breeds in silage DM intake were accounted for by indicator variables, also called dummy variables, related to $LW^{0.75}$ estimated on the basis of the dataset from the Norwegian Breeders’ Association Test Station, by using the SAS Proc Reg (SAS Institute Inc 1999b):

$$SDMI_{act} (g \text{ kg}^{-1} \text{ LW}^{0.75} \text{ d}^{-1}) = SDMI_{pot} \times f(CI) + 0.00246 \times LW_{t-1}^{0.75} - 0.00611 \times LW_{t-1}^{0.75} \text{ Limousin}$$

In search for an appropriate equation for prediction of daily LW gain (DLWG) we chose to find a formula for all the five breeds with the least bias in the residuals, by several runs of SAS Proc Reg (SAS Institute Inc 1999b) and inspection of the deviation plots. The resultant equation, based on the $LW_{t-1}$ and the current days total energy intake, was:

Table 2. General overview of the breed specific differences in the model components, algorithms, of silage dry matter (DM) intake, daily live weight (LW) gain, EUROP conformation (EUROP) and fatness score (FAT). The + symbol indicates a higher value than average, the – symbol indicates a lower value than average.

<table>
<thead>
<tr>
<th>Breed</th>
<th>Silage DM intake</th>
<th>Daily LW gain (^a)</th>
<th>EUROP</th>
<th>FAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angus</td>
<td>+</td>
<td>“Early maturing”</td>
<td>Average</td>
<td>+</td>
</tr>
<tr>
<td>Charolais</td>
<td>–</td>
<td>“Charolais”</td>
<td>+</td>
<td>Average</td>
</tr>
<tr>
<td>Hereford</td>
<td>Average</td>
<td>“Early maturing”</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Limousin</td>
<td>–</td>
<td>“Limousin”</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Simmenttal</td>
<td>Average</td>
<td>“Charolais”</td>
<td>Average</td>
<td>Average</td>
</tr>
</tbody>
</table>

\(^a\) corresponding to the INRA tables (Garcia et al. 2007)
DLWG (g d⁻¹) = a₀ + a₁ × LW⁻¹ + a₂ × LW⁻¹.8 + a₃ × FUb + a₄ × FUb¹.5 + a₅ × FUb × LW⁻¹ + a₆ × LW⁻⁰.75

where FUb is the total daily net energy intake, the sum of the FUb in the SDMI act and the FUb in the daily concentrate ration, and the parameters a₀ to a₆ are breed dependent (Table 3). The LWs of the bulls were then obtained by integrating the respective DLWG from the typical weaning weights for the five breeds. The typical weaning weights of the bulls where derived from the Norwegian Beef Cattle Recording System: 272 kg for Angus; 294 kg Charolais; 259 kg Hereford; 287 kg Limousin and 310 kg for Simmental. The parameters in Table 3 should not be given any biological meaning beyond that the sum of the LW related variables and the sum of the FUb variables in Equation 4 reflects the diminishing return of the energy in the feed ration with increasing weight of the bull and with increasing total daily energy intake.

In the model daily values for EUROP conformation (e.g. Bohuslávek 2000) and fatness score were calculated on the basis of the daily value carcass weight (CW), expressed as the state variable LW multiplied with the daily value of the dressing percentage/100, and the time form birth, expressed as the slaughter age (SA). Of the 94,661 bulls in the beef cattle recording system, the crossbreeds with less then ¾ of the respective breeds were excluded from the dataset. Bulls that had higher slaughter age than 24 months and bulls with very low carcass weights compared to slaughter age were also excluded. Bulls slaughtered at greater than 24 months of age are most likely breeding bulls, and not fed specifically for finishing. The remaining numbers of bulls of each breed were then: Angus, 2026; Charolais, 4691; Hereford, 3512; Limousin, 2448; Simmental, 1002. Correlations both for EUROP-conformation (EUROP) and fatness (FAT) with carcass weight (CW) and slaughter age in days (SA) were assumed, the interaction term CW × SA was excluded from the Equations 5 and 6 at p > 0.1 significance level by using linear stepwise regression in SAS Proc Reg (SAS Institute Inc 1999b); and the differences among the five breeds were accounted for by indicator variables related to their respective CW:

EUROP (dimensionless) = 2.38788 + 0.01959 × CW
− 0.00185 × SA − 0.00257 × CW_{Hereford} + 0.00259 × CW_{Charolais} + 0.00697 × CW_{Limousin} \[5\]

FAT (dimensionless) = 1.88954 + 0.01532 × CW
− 0.00367 × SA + 0.00993 × CW_{Angus} + 0.01084 × CW_{Hereford} − 0.00161 × CW_{Limousin} \[6\]

The EUROP-conformation is scaled in integer from 1 to 15 where 1 equals to P– and 15 equals to E+. Fatness is scaled in integer from 1 to 15 where 1 equals to 1– and 15 equals to 5+.

The dressing percentage (DP) is not recorded in the Norwegian Beef Cattle Recording System. However, an equation assuming a correlation between DP and EUROP-conformation, using a continuous scale, as suggested by Clason and Stenberg (2008) was used in the model. This equation was based on data from Danish research (Tinderup and Boysen 2004).
\[ DP(\%) = 1.532 \times EUROP + 41.349 \quad [7] \]

To estimate beef prices, premiums, and governmental payments, a standard Norwegian price table was included in the model. The base beef price used in the model is 35 Norwegian kroner (NOK) kg\(^{-1}\) CW; this price applies for a bull of 300 kg CW, EUROP-conformation of O+ and no fatness deduction. The model beef price is daily updated and varies due to the current weight classes and EUROP-conformation, and there is deduction due to fatness classes higher than 3−. For bulls with CW between 225 kg and 350 kg, and EUROP-conformation of O− or better and no fatness deduction, a premium of 1.5 NOK kg\(^{-1}\) CW is given. At EUROP-conformation of the R classes a premium of 1.5 NOK is given regardless of weight class, and at the UE classes a premium of 3.5 NOK is given. The model also accounts for the seasonal variation in the beef price of up to 2 NOK kg\(^{-1}\) CW reflecting the variation in supply: The peak of the seasonal beef price variation is in June and the low-points are January 1 and July 31. The governmental payments of 393.5 NOK per bull received on January 1 and July 31 were also included in the model.

Simulations and optimisation

An iterative search method in the computer software Powersim Solver (Saleh and Myrtevit 2004, Bonesmo 1999) was used to find the concentrate levels, slaughter ages and carcass weights that maximized the mean daily return (MDR) of the finishing period; i.e. the decision variables were: concentrate level, g kg\(^{-1}\) LW\(^{0.75}\) d\(^{-1}\), slaughter age, days, and carcass weight, kg. The mean daily return was calculated as the slaughter return minus the total feeding costs and the weaner price divided by the numbers of days of the finishing period. Standard Norwegian weaner price was used (Deblitz et al. 2008), and the extra weaner cost of 1500 NOK per bull for Charolais, Limousin and Simmental was added to the weaner cost. The concentrate price was set to 2.65 NOK kg\(^{-1}\). As a base for the optimisation, typical numbers for birth date, March 15; weaning date, September 30; and weaning weights (Table 3) for the bulls of the five breeds were used. To reflect the on farm variation in the silage quality and the silage price, combinations of a low silage energy concentration (800 FU\(_b\) kg DM\(^{-1}\)), a higher silage energy concentration (940 FU\(_b\) kg DM\(^{-1}\)), a low silage price (1 NOK FU\(_b\) kg\(^{-1}\)) and a higher silage price (2 NOK FU\(_b\) kg\(^{-1}\)) were investigated. Stochastic simulations (Hardaker et al. 2004, 157–181), were conducted using Powersim Solver to find a probability assessment of the variation in MDR due to the variation in the EUROP-conformation and the fatness classes as revealed from the cattle recording system. The sampling method used was Latin Hypercube and the number of iterations was 1000. An iteration represents one draw of a sequence of the two random variables: the error terms in the equations for EUROP-conformation (Equation 5) and fatness (Equation 6) represented by the standard deviations. The standard deviations were found to be non-correlated and assumed to be normal distributed with expected values = 0 and were estimated to 0.49 (dimensionless) for the EUROP conformation and 0.61 (dimensionless), for the fatness score.

To evaluate the results of the risk analysis the concept of stochastic dominance developed by Hadar and Russell (1969) and Hanoch and Levy (1969), was applied. There are several stochastic dominance criteria, associated with different sets of preference assumptions. This study used first (FSD) and second (SSD) degree stochastic dominance. The FSD implies that decision makers prefer more of an outcome to less. Statistically, the rule means that alternative A is preferred to alternative B if, for every possible level of return, the probability of getting a return that high is never better for B than for A. The second rule, SSD, states that decision makers are risk averse as well as preferring more to less. Alternative A is preferred to alternative B by SSD if the curve of the cumulative area under the cumulative distribution function (CDF) for alternative A lies everywhere below and to the right of the corresponding curve for alternative B. In order to determine whether a relation of stochastic dominance holds, the distributions have to be characterised by their CDFs.
Results

The combined silage intake model gave an applicable estimation of the silage intake (Fig. 1), the root mean square error (RMSE) between measured and estimated silage intake ranged from 0.45 kg d\(^{-1}\) to 0.78 kg d\(^{-1}\). This was lower than the RMSE between measured and estimated silage intake of 0.99–1.0 achieved on the same data by using the silage intake equation of the AFRC (AFRC 1993); the better performance can be attributed to the adjustment of the equation of potential silage DM intake (Equation 1) to the timothy and meadow fescue based silage. The silage intake model performed best on the data of the feeding seasons 2004–2005 and 2006–2007; the silage used in those feeding seasons had higher energy concentration than the silage used in the other two seasons (Table 1).

The simulations of live weight (LW) were also very convincing for the feeding seasons 2006–2007 and 2004–2005 (Fig. 2), for those seasons the RMSE ranged from 4.0 kg to 13.0 kg among breeds. For these seasons there was a tendency to underestimate the LW of the Angus and Hereford bulls, the LW of the Charolais bulls were slightly overestimated. Over all four feeding seasons the simulated LW of the Limousin bulls corresponded best to the measured value. The Limousin bulls had the lowest silage DM intake relative to LW (Equation 3), thus the error in the silage DM intake would be less notable for bulls of this breed. There were considerable underestimations of LW of the Charolais bulls for the feeding seasons of 2003–2004 and 2005–2006 and for Simmental bulls the feeding seasons of 2005–2006. For these years the DM intake, hence LW gain, was underestimated because it is suspected there are errors in the silage DM intake simulations. Thus, the INRA feeding tables based equation of LW gain (Equation 4) might be considered as reliable for the Norwegian bull phenotypes of the five beef breeds. The overall performance of the model to simulate the LW of the bulls was good. However, for all years there was a tendency to underestimate the LWs of Angus and Hereford bulls at higher weights; the INRA tables (Garcia et al. 2007) of the early maturing breeds do not fully reflect the growth pattern of Angus and Hereford bulls.

For bulls of all the five breeds an optimal concentrate level to maximise average daily return for both silage energy concentrations and both prices was determined (Table 3). Among all the five breeds the Limousin bulls had the highest estimated mean daily return and Hereford bulls the lowest estimated mean daily return from 20 g concentrate kg\(^{-1}\) LW\(^{0.75}\) for the 940 FUb kg\(^{-1}\) silage DM, and from 40 g concentrate kg\(^{-1}\) LW\(^{0.75}\) for the 800 FUb kg\(^{-1}\) silage DM (Fig. 3). The difference between the bulls of Angus and Hereford may mainly be caused by the 13 kg lower weaning weight of the Hereford bulls (Table 3), but may also be attributed to the higher silage intake capacity (Equation 3) and the somewhat better confirmation (Equation 5) of Angus bulls than of the Hereford bulls. For both the silage qualities the main difference in average daily return in relation to the feed ration concentrate level (kg\(^{-1}\) LW\(^{0.75}\)) among the breeds was between bulls of Angus, Hereford and bulls of Charolais, Limousin, Simmental, where the latter group over a larger range of concentrate levels have considerable higher mean daily return. Note that that the lines between the points in Figure 3 are
Fig. 2. Measured and simulated live weights (LW) of bulls of five beef breeds at four 21 weeks feeding periods
Fig. 3. Estimated optimal values of mean daily return in Norwegian kroner (NOK d⁻¹), age at end of finishing, and carcass weights of bulls of five beef breeds for five concentrate levels related to metabolic weight (LW⁰.⁷⁵) for two silage energy concentrations and one silage price, A: 940 feed unit beef (FUb) kg⁻¹ dry matter (DM) silage and 1.0 Norwegian kroner (NOK) 1000 FUb⁻¹, B: 800 FUb kg⁻¹ DM silage and 1.0 NOK 1000 FUb⁻¹.
interpolations, due to stepwise change in price due to discrete variables as weight classes, EUROP-conformation classes and seasonal change in base beef price the change in mean daily return in relation to concentrate level will not actually be a continuous line.

For the 940 FUb kg\(^{-1}\) DM silage the highest estimated mean daily return was at 22 g concentrate kg\(^{-1}\) LW\(^{0.75}\) for the Angus bulls and 26 g concentrate kg\(^{-1}\) LW\(^{0.75}\) for the Hereford bulls, for the bulls of those breeds an increase in concentrate level above 50 g concentrate will result in a greater reduction in mean daily return than a situation where there was no concentrate in the feed ration. For the bulls of Charolais, Limousin and Simmental the highest estimated mean daily return was from 34 to 43 g concentrate kg\(^{-1}\) LW\(^{0.75}\). For all breeds and all concentrate levels (g kg\(^{-1}\) LW\(^{0.75}\)) the mean daily return was substantially lower for the the 800 FUb kg\(^{-1}\) DM silage than for the 940 FUb kg\(^{-1}\) DM silage; the mean daily return was even negative at 0 g concentrate kg\(^{-1}\) LW\(^{0.75}\) for Charolais, Limousin and Simmental (Fig. 3). For Angus and Hereford bulls the highest mean daily return was achieved slightly above 40 g concentrate kg\(^{-1}\) LW\(^{0.75}\). However, the mean daily return for these breeds was relatively stable between 20 and 60 g concentrate kg\(^{-1}\) LW\(^{0.75}\). For Limousin bulls, the optimum mean daily return was close to 60 g concentrate kg\(^{-1}\) LW\(^{0.75}\), and for Charolais or Simmental bulls the optimum was slightly below 55 g concentrate kg\(^{-1}\) LW\(^{0.75}\). For these Euro breeds the mean daily return will be considerably lower with a small change in concentrate level. Going from 1 to 2 NOK 1000 FUb\(^{-1}\) for the 800 FUb kg\(^{-1}\) DM silage, the mean daily return for bulls of all the breeds except for Limousin will be 3 NOK lower, for the Limousin bulls it will be lowered by 1 NOK only. This is caused by the lower silage intake capacity of the Limousin bulls compared to the bulls of the other breeds. Compared to the highest quality silage the 800 FUb kg\(^{-1}\) DM results in a higher slaughter age and higher carcass weights for Charolais, Limousin and Simmental, whereas Angus and Hereford had the same slaughter age but lower carcass weights (Table 3). A doubling of the silage price for the lowest quality silage resulted in a slightly higher daily live weight gain but lower carcass weights, i.e. a less intensive production.

When the effect of variation in EUROP confirmation and fat was assessed for the optimal strategies (Table 3), the 940 FUb kg\(^{-1}\) DM silage of 1 NOK 1000 FUb\(^{-1}\) had first degree stochastic dominance for all five breeds (Fig. 4), because at every possible probability level the value of returns of the 940 FUb kg\(^{-1}\) DM silage of 1 NOK 1000 FUb\(^{-1}\) is greater than that of the other combinations of silage prices and energy concentrations. The highest quality silage of 2 NOK 1000 FUb\(^{-1}\) dominated the lower quality silage of 1 NOK 1000 FUb\(^{-1}\) for Limousin bulls with first degree dominance and for Charolais with second degree dominance. Although quite similar in risk, the less expensive lower quality silage resulted in second degree stochastic dominance for Angus and Simmental bulls when compared to the more expensive higher quality silage. For Hereford bulls the same comparison resulted in first degree stochastic dominance. The optimal strategy for the higher quality silage of 1 NOK for Limousin bulls had the smallest variation in mean daily return (4.4 NOK), whereas the higher quality silage of 2 NOK had the largest variation (8.7 NOK).

**Discussion**

The supply of locally produced beef has been decreasing in Norway for the last 10 years. Despite increases in suckler cow based beef production, this boost to production has not been enough to account for the decrease in the dairy based beef production (Statistics Norway 2008). One reason that could explain the lack of growth in suckler cow based beef production is that the profitability of that production is too low. A tool that can assist farmers in improving the management practices and increase the profitability of beef production under Norwegian conditions could help halt the decline in beef production. This paper describes such a tool that has been developed to simultaneously optimise feeding and timing of slaughtering in beef finishing. The tool is...
Fig. 4. Risk analysis, cumulative distribution functions: the variation in mean daily return (MDR) in Norwegian kroner (NOK) of finishing of bulls of five breeds due to variation in EUROP and fat conformations scores for higher silage energy concentration and lower price silage, 940 feed unit beef (FUb) kg⁻¹ dry matter (DM) silage of 1 NOK 1000 FUb⁻¹, compared with the risk at either lower silage energy concentration (800 FUb kg⁻¹) or higher price (2 NOK 1000 FUb⁻¹).
Table 4. Conditions for optimization (to the left): two levels of silage energy concentration in g feed unit beef (FUb) per kg dry matter (DM), two silages prices in Norwegian kroner (NOK) per FUb, and breed specific live weight (LW) at weaning. Estimated optimal characteristics (to the right): Mean daily return (MDR) in NOK per day, concentrate level in g concentrate per kg LW^{0.75}, slaughter age in months, carcass weight (CW) in kg, average daily live weight gain of the finishing period (DLWGavg) in kg per day, dressing percentage, beef price in NOK kg^{-1}, and EUROP conformation (EUROP) and fatness score (FAT) in integer.

<table>
<thead>
<tr>
<th>Silage Conditions</th>
<th>Energy concentration FUb kg^{-1} DM</th>
<th>Price NOK FUb^{-1}</th>
<th>Breed</th>
<th>LW at weaning</th>
<th>Estimated Beef Production Characteristics</th>
</tr>
</thead>
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<tr>
<td></td>
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<td>MDR NOK d^{-1} Concentrate level g kg^{-1} LW^{0.75} d^{-1} Slaughter age Months</td>
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<tr>
<td>940</td>
<td>1</td>
<td></td>
<td>Angus</td>
<td>272</td>
<td>13 22 13.9 283 1.20 52 38.7 7 7</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Angus</td>
<td>272</td>
<td>8 37 12.5 268 1.33 52 38.7 7 7</td>
</tr>
<tr>
<td>800</td>
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<td>Angus</td>
<td>272</td>
<td>9 43 14.0 268 1.08 52 39.2 7 7</td>
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<td></td>
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<td></td>
<td>Angus</td>
<td>272</td>
<td>5 51 14.0 276 1.14 52 39.2 7 7</td>
</tr>
</tbody>
</table>

*a The Beef Cattle Recording System (typical numbers for the years 2001–2007)

*b Optimization range: 350–650 d, 0–80 g concentrate kg^{-1} LW^{0.75}
already used by advisers in the feed industry, which in collaboration with the farmer and his knowledge of the production data for his farm, can indicate the optimal tactical decisions regarding quantity of feed, the duration of the finishing period, and the carcass weight for bulls of the five most common beef breeds in Norway. As with the model for Irish beef finishing of Kilpatrick and Steen (1999) our model of the beef cattle production process also comprises two components: the feed intake and the effects of feed energy intake on growth rate. The satisfactory prediction by our approach of these two components, demonstrated in this paper, provides the necessary basis for the estimation of the most economic level of concentrate feeding to achieve the growth and quality of carcass composition required. Although the model was developed for use as a tactical decision support tool at individual farm level, the model in this work is used in combination with typical numbers of birth dates, weaning dates and weights of the bulls of the five breeds to find general recommendations or “rules of thumb” in beef finishing under Norwegian conditions.

Our estimated optimal slaughter ages and carcass weights indicates that a substantial intensification of the feeding in the finishing period is warranted for the bulls of all the five breeds. Current farming practice in Norway for the five major breeds studied was for the slaughter age to be more than two months longer with carcass weights lighter than what the results of our optimisation recommend (Animalia 2008). However, our estimated slaughter ages for bulls of Angus, Hereford and Limousin are in accordance with the Danish practice (Dansire 2006). Our estimated optimal slaughter weights of Angus and Hereford bulls are also close to those of Danish practice, whereas the estimated optimal slaughter weight for Limousin bulls is somewhat higher. The estimated optimal slaughter ages and carcass weights for bulls of Charolais and Simmental were somewhat longer and considerable higher than the Danish average figures for those breeds; the Danish bulls of Charolais and Simmental seems to achieve better EUROP-conformation scores at lower carcass weights than what could be found for the bulls of those breeds in the Norwegian Cattle Recording System.

As noted by Pihamaa and Pietola (2002) the optimisation procedure detects the break points: “the optimal timing of slaughter is at the point where the bull reaches the quality adjustment (price increase) after reaching the minimum weight class”. The estimated carcass weights and slaughter ages must thus be considered as limits. As examples: Based on statistics of the Norwegian cattle recording system, the Limousin bulls reach the highest quality premium at carcass weights lower than 350 kg; the Limousin bulls can achieve both the premium for optimal carcass size (<350 kg) and the highest quality premium and should thus be slaughtered before the carcass weight exceeds 350 kg. In contrast Norwegian Charolais bulls do not reach the highest quality premium until carcass weight is greater than 350 kg, and must thus be slaughtered later. The estimated high carcass weight and long finishing period for the Charolais bulls is also determined by the seasonal variation in price. Our optimisation is based on a typical calving date, and at the time the Charolais bull reaches the highest quality premium, the seasonal price is at its lowest, thus the finishing period has to be prolonged to achieve a higher price. However, the similarity of the ranking among the breeds in slaughter age and carcass weight between our estimated values for bulls and the values for steers estimated by Williams and Bennet (1995) suggest that there are some general and simple “rules of thumb”. Bulls and steers of Angus and Hereford breeds should have lower carcass weights and slaughter ages than bulls and steers of Simmental breeds that should have a high carcass weight. Bulls and steers of Limousin breeds should be somewhere between Angus/Hereford and Simmental in carcass weight. Both the estimated values of steers (Williams and Bennet 1995) and the Danish values for bulls (Dansire 2006) suggest that the carcass weight and slaughter age of Charolais should be close to those of Limousin. Our estimated values for Charolais bulls are, however, closer to those of the Simmental bulls than to those of Limousin bulls.

Similar to the conclusion of Pihamaa and Pietola (2002) our optimisation results show that the price of silage in general does not affect the optimal slaughter age and carcass weights but it affects
farmer returns and animal feeding. When the price of silage is doubled from one to two NOK per FUb the optimal carcass weights and slaughter ages remains practically unchanged but the farmers mean daily returns decreased by 40 to 50 % for the Angus and Hereford bulls, 20 to 25 % for the Charolais and Simmental bulls, and 5 to 15 % for the Limousin bulls. The ranking in the decrease in mean daily return among the breeds reflects the different ratios of silage to concentrate in the feed rations of the breeds. The differences among the breeds optimal silage to concentrate ratios is a consequence of differences in silage intake capacity, potential daily live weigh gain, and deposition of fat.

Looking at the finishing period only, our work implies that bulls of Limousin origin are the best choice of breed based on profit per day. The finishing of Limousine bulls also had the lowest variation in EUROP-conformation and fatness. However, at the silage of 800 FUb kg DM\(^{-1}\) and 1 NOK FUb\(^{-1}\) the finishing of Charolais bulls could generate the similar level of return per day (Fig. 4), indicating the potential for similar performance in the finishing phase of the breeds Charolais and Limousin as found by Williams and Bennet (1995).

Although bulls of Limousin origin achieved the highest profit per day in our simulations, our work does not disqualify the other breeds as suitable under Norwegian conditions. The fact that all the five breeds are present in significant numbers in Norway today indicates that they all have valuable qualities for our conditions. Beef production based on suckler cow breeds has been established in Norway as well as in Finland and Sweden for the last twenty years (Statistics Norway 2008, Tike 2007, Jordbruksverket 2005). Thus it is a relatively new production system in most of the Nordic countries. The farmers dealing with beef production based on suckler cow breeds thus have to find the best management system and the best choice of breed, or cross breeding system, based on knowledge generated for other environmental conditions. Among several factors that have to be taken into account is the cow-calf part of the production. Thus, decision support systems for the cow-calf part, as for example the model of Tess and Kolstad (2000) should also be develop for our conditions.

The intensification of the finishing phase as recommend in the current work is, however, a requisite of profitable beef production under our conditions. In a Nordic production environment the standard is that cattle are raised indoors for most of the time and the matured animal has to be culled to enable stable space for a new calf. Beef production using steers is regarded as an extensive alternative to bull feeding, but if the capacity of the barn will be the main constraint, the farm income is optimized by maximisation of net returns per steer per time unit in the barn. Under such circumstances Nielsen and Kristensen (2007) recommended an intensive finishing even on steers.

High net return in beef finishing is also valuable in the production of public goods. The beef production is the base for the multi-functionality of European grasslands (Sarzeaud et al. 2008). Grassland-cattle systems can be carbon sinks (Soussana et al. 2007). In France the sequestering of carbon in grassland is estimated to compensate for half of the ruminant emissions of methane, nitrous oxide and nitrogen related to the livestock transforming grass to meat (Sarzeaud et al. 2008). Further, the role of grasslands appears significant in the maintenance of biodiversity and landscape management. Most of the meadows have a good vegetation diversity compared with mono-cropping. This is due to the long-term pastoral practices, which guarantee the maintenance of a large variety of grass species but also insects, micro-organisms, and other fauna such as earthworms. To ensure the continuation of these positive public good features, high profitability in beef finishing is vital. Thus, our model may also contribute to the production of goods available for everyone and without special quantitative or qualitative limits.

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References


Performance of growing dairy bulls offered diets based on silages made of whole-crop barley, whole-crop wheat, hairy vetch and grass

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The present experiment was conducted to study diet digestibility, feed intake, animal performance and carcass characteristics of growing dairy bulls offered diets based on whole-crop barley, a mixture of whole-crop barley and hairy vetch (Vicia villosa Roth.) or a mixture of whole-crop wheat and hairy vetch relative to moderate digestible grass silage-based diet. The feeding experiment with 24 Finnish Ayrshire and 8 Holstein-Friesian bulls included 4 forage feeding treatments: grass silage (G), whole-crop barley and hairy vetch mixture silage (BHV), whole-crop wheat and hairy vetch mixture silage (WHV) and whole-crop barley silage (B). In all treatments animals were offered silage ad libitum. The amount of concentrate supplementation was 36 g (W0.75) kg-1 per animal per day for all treatments. The concentrate ration included rolled barley and rapeseed meal. Differences between the treatments were compared using an a priori test (Dunnett’s test) so that comparison of the diets was based on the G diet. The animals were fed the experimental diets from day 240 to finish at day 505 of age. During the experiment the average concentrate proportions of G, BHV, WHV and B diets were 437, 424, 426 and 423 g dry matter (DM) (kg DM)-1, respectively. There were no significant differences in silage DM intake or in the total DM intake (DMI) (kg DM d-1) between treatments. However, DMI kg-1 W0.75 tended to be 3.5% higher (p = 0.09) in the B diet than in the G diet. Due to increasing energy intake, the gain of the bulls was higher with the G diet than with the WHV diet (p < 0.05). BHV and B diets did not differ from the G diet in gain. Treatments had no significant effect on the dressing proportion or carcass conformation. The carcass fat score of WHV bulls was 29% lower (p < 0.05) than that of the G bulls, but BHV and B diets did not differ from the G diet in carcass fatness. The feed conversion rate (DM intake kg-1 carcass gain) of the bulls was better (p < 0.001) and protein conversion (g AAT kg-1 carcass gain) tended to be better (p = 0.07) with the G diet than with the WHV diet. BHV and B diets did not differ from the G diet in any feed conversion parameters. It can be concluded that replacing moderate digestible grass silage with whole-crop wheat and hairy vetch mixture silage decreased the carcass gain of growing dairy bulls due to lower energy intake and poorer feed conversion. Instead, replacing moderate digestible grass silage with whole-crop barley or with whole-crop barley and hairy vetch mixture silage resulted in no differences in the performance or carcass characteristics parameters of growing dairy bulls.

Key-words: Beef production, dairy bulls, whole-crop silages, hairy vetch, Vicia villosa Roth, feed intake, growth rate
Introduction

Grass silage is the main forage for growing cattle in Finland. However, increasingly other ensiled forages, such as different whole-crop silages, are being used due to their potentially lower costs. In addition, recent advances in plant breeding, agronomic practices and forage conservation technologies are expanding opportunities for these alternative crops (Walsh et al. 2008a) and nowadays small-grain cereals are widely grown for animal feed in temperate climates. An economic advantage of harvesting cereals as whole-crops is that farmers can use the same machines they use for making grass silage. However, direct cut harvest of the crop to decrease field losses at later maturity stages is recommended. Grains, on the other hand, need different types of machines and the investment costs involved may be high. Furthermore, drying and storage of grains can be costly processes for the farmer. Harvesting cereals at an earlier maturity stage compared to grain maturity increases the radiation to a developing undersown crop, and can be beneficial for weed control reasons (Wallsten 2008). In Finland, barley (Hordeum vulgare) is the dominant small-grain species utilized for whole-crop production (Ahvenjärvi et al. 2006), but oats (Avena sativa) and wheat (Triticum aestivum) are also used. In organic farming systems, annual legumes are often sown with cereals. The objective of mixed cultivation is to decrease the need for inorganic nitrogen fertilization and to improve the feeding value of harvested forage. Forage pea (Pisum sativum L.), common vetch (Vicia sativa L.) and hairy vetch (Vicia villosa Roth.) are current annual legumes in Finland.

The digestibility of whole-crop silages is highly dependent on the proportion of straw and is often lower than that of good-quality grass silage (Abdalla et al. 1999, Sinclair et al. 2003). However, the lower digestibility is largely compensated for by higher dry matter intake (DMI) such that energy intake is maintained (Abdalla et al. 1999, Sinclair et al. 2003). In a review of experiments where whole-crop wheat silage was included in grass silage-based diets for lactating dairy cows, Keady (2005) concluded that feed intake increased by 2–3 kg DM d⁻¹ but that there were no beneficial effects on milk yield or yield of fat plus protein. An accompanying compilation of seven experiments with finishing beef cattle concluded that the inclusion of whole-crop wheat silage in grass silage-based diets increased forage intake by 1.4 kg DM d⁻¹, but did not alter animal performance (Keady 2005). However, there is lack of information on the effects of mixtures of whole-crop cereal and hairy vetch on the performance of growing dairy bulls relative to a grass silage-based diet. Therefore, the present experiment was conducted to study diet digestibility, feed intake, animal performance and carcass characteristics of growing dairy bulls offered diets based on silage made from (1) whole-crop barley, (2) mixture of whole-crop barley and hairy vetch, or (3) mixture of whole-crop wheat and hairy vetch relative to moderate digestible grass silage-based diet.

Material and methods

Animals, diets and experimental design

The feeding experiment with 24 Finnish Ayrshire and 8 Holstein-Friesian bulls was conducted in the experimental barn of the North Ostrobothnia Research Station of MTT Agrifood Research Finland (Ruukki, 64°44′N, 25°15′E). It started in November 2000 and ended in August 2001 (duration of experiment 265 d). The experimental procedures were evaluated and approved by the Animal Care and Use Committee of MTT Agrifood Research Finland. All animals were purchased from local dairy farms. Before the beginning of the present feeding experiment they were housed and fed individually in straw-bedded pens measuring 1.15 × 2.00 m until 120 days of age and fed milk, hay, silage and concentrates (barley and rapeseed meal (RSM)). From 120 until 240 days of age the animals were housed in tied stalls and fed grass silage (ad libitum) and concentrates (barley and RSM; limited to a maximum of 3 kg DM per head daily).
At the beginning of the present experiment the animals (initial live weight (LW) 319±28.5 (mean ± SD) kg and age 240±2.9 days) were divided into eight blocks of four animals by LW and breed so that there were six Ayrshire blocks and two Holstein-Friesian blocks. Age was not taken into account in the blocking because of the small variation in age. Within each block one randomly selected animal was chosen for each treatment. The bulls were placed in an insulated barn in adjacent tie-stalls. The width of the stalls was 70–90 cm for the first four months and 113 cm until the end of the experiment. The bulls were tied with a collar around the neck, and a 50 cm long chain was attached to a horizontal bar 40–55 cm above the floor. The floor surface was solid concrete under the forelegs and metal grids under the hind legs. No bedding was used on the floor.

The animals were fed three times per day (at 0800, 1200 and 1800 h). Refused feed was collected and measured at 0700 h daily. The bulls had free access to water from an open water bowl during the experiment. One animal was excluded from the study due to several occurrences of bloat and another due to hoof problems. There was no reason to suppose that the diets had caused these problems. The four feeding treatments were grass silage (G), whole-crop barley and hairy vetch mixture silage (BHV), whole-crop wheat and hairy vetch mixture silage (WHV) and whole-crop barley silage (B).

The grass silage used was the primary growth of timothy (Phleum pratense) and meadow fescue (Festuca pratensis) sward, cut using a mower conditioner, wilted for 6h, and then harvested using a precision-chop forage harvester. Grass silage was ensiled in bunker silos with a formic acid-based additive (AIV-2 Plus: 760 g formic acid kg⁻¹, 55 g ammoniumformate kg⁻¹; supplied by Kemira Ltd., Finland) applied at a rate of 5 l t⁻¹ of fresh grass. All whole-crop silages used in the feeding experiment were harvested at the early dough stage (growth stage Z83 on Zadoks scale; Zadoks et al. 1974) of the cereal using a direct-cut flail harvester. Harvest dates of grass silage, BHV, WHV and B silages were June 25, August 2, August 27, and August 5, respectively. Also the BHV, WHV and B silages were ensiled in bunker silos with the same formic acid-based additive as for the grass silage applied at a rate of 5 l t⁻¹ of fresh silage. The barley cultivar used in the BHV mixture was Artturi (seeding rate: 120 kg ha⁻¹) and the hairy vetch cultivar was Viola (seeding rate: 34 kg ha⁻¹). Respectively, the wheat cultivar used in the WHV mixture was Mahti (206 kg ha⁻¹) and the hairy vetch cultivar was Viola (34 kg ha⁻¹). The barley cultivar used in the B silage was Artturi (seeding rate: 200 kg ha⁻¹). According to botanical determinations (ten 25 cm × 50 cm forage samples were collected from both BHV and WHV fields) before harvesting, BHV contained barley (510 g DM (kg DM)⁻¹), hairy vetch (410) and other plants (80). Respectively, WHV contained wheat (410), hairy vetch (580) and other plants (10).

In all treatments the animals were offered silage ad libitum (proportionate refusals 5%). The amount of the concentrate supplementation was 36 g (W₀.₇₅⁻¹) per animal per day for all treatments, and the target for average daily concentrate level during the experiment was 400 g DM (kg DM)⁻¹. Silage and concentrate were fed separately. The concentrate ration for all treatments included rolled barley and RSM so that RSM supplementation was 440 g DM per animal daily. The daily concentrate ration also included 150 g of a mineral mixture (Tähkä Apekivennäinen: delivered by Feedmix Ltd., Koskenkorva, Finland). A vitamin mixture (Xylitol ADE-Vita: delivered by Suomen Rehu Ltd., Espoo, Finland) was given 50 g per animal weekly. The compositions of mineral and vitamin mixtures used are fully described by Huuskonen et al. (2007a) and Huuskonen (2009).

**Procedures and sample analyses**

Silage samples for chemical analyses were taken daily, pooled over periods of four weeks and stored at −20°C. Thawed samples were analysed for DM, organic matter (OM), crude protein (CP), neutral detergent fibre (NDF), starch, in vitro DM digestibility (DMD) and fermentation quality (pH, lactic
and formic acids, volatile fatty acids, soluble and ammonia N content of total N). Barley and RSM sub-samples were collected weekly, pooled over periods of four weeks and analysed for DM, OM, CP and NDF. The chemical analyses of DM, ash, CP and NDF were made as described by Ahvenjärvi et al. (2000). Starch was determined as described by Bach Knudsen et al. (1987). Silage samples were analysed for in vitro DMD by the method described by Friedel (1990) and for fermentation quality by electrometric titration described by Moisio and Heikonen (1989).

Diet apparent digestibility was determined for all animals when the bulls were 503±28 kg LW, on average. Feed and faecal samples were collected twice a day (at 0700 and 1500 h) during the collection period (5 d) and stored frozen prior to analyses. The samples were analyzed for DM, ash, CP and NDF as described above. Diet digestibility was determined using acid-insoluble ash (AIA) as an internal marker (van Keulen and Young 1977).

### Calculations and carcass measurements

The ME contents of the feeds were calculated according to Finnish feed tables (MTT 2006). The ME value of the silages was calculated as 0.16 × D-value (MAFF 1981). The ME values of the concentrates were calculated as described by Schiemann et al. (1972) and MAFF (1984). The digestibility coefficients of concentrates were taken from Finnish feed tables (MTT 2006). The supply of amino acids absorbed from the small intestine (AAT) and protein balance in the rumen (PBV) were calculated according to the Finnish feed tables (MTT 2006).

The animals were weighed on two consecutive days at the beginning of the experiment, thereafter approximately every 28 days. Before slaughter they were weighed again on two consecutive days. The target for average carcass weight in the experiment was 300 kg. The live weight gain (LWG) was calculated as the difference between the means of initial and final weights. The estimated rate of carcass gain was calculated by assuming an initial carcass weight of 0.50 of initial LW which was used also in previous studies by Huuskonen et al. (2007b, 2008, 2009). After slaughter in a commercial meat plant carcasses were weighed hot. Cold carcass weight was estimated as 0.98 of hot carcass weight. Dressing proportions were calculated from the ratio of cold carcass weight to final live weight. Carcass conformation and carcass fat score were determined according to the EUROP classification (Commission of the European Communities 1982). For conformation, development of carcass profiles, in particular the essential parts (round, back, shoulder), was taken into consideration according to the EUROP classification (E: excellent, U: very good, R: good, O: fair, P: poor), and for fat cover degree the amount of fat on the outside of the carcass and in the thoracic cavity was taken into account using a classification range from 1 to 5 (1: low, 2: slight, 3: average, 4: high, 5: very high). Each level of conformation scale was subdivided into 3 subclasses (O+, O, O-) to a transformed scale ranging from 1 to 15, 15 being the best conformation.

### Statistical Methods

The experiment was set up according to a randomized complete block design with animal as an experimental unit. The results are shown as least squares means, because the records from two excluded animals were not replaced. The data were subjected to analysis of variance using the SAS mixed model procedure. The model used was

\[ y_{ij} = \mu + \beta_j + \alpha_i + e_{ij} \]

where \( \mu \) is the overall mean, \( \beta_j \) is the random effect of block \( (j=1, \ldots, 8) \), \( e_{ij} \) is the random error term and \( \alpha_i \) is the fixed effect of treatment. Differences between the treatments were compared using an a priori test (Dunnett’s test) so that comparison of the diets was based on the G diet.
Results

Diets

Dry matter yields of BHV and WHV were 3 540 and 8 010 kg ha⁻¹. The difference in BHV and WHV yields was probably affected most by the severe lodging of BHV during growth period. The lodging probably reduced both the maximum obtainable yield and harvested yield. All silages were restrictively fermented and of good quality in terms of low pH and low concentrations of fermentation acids and ammonium-N (Table 1). Whole-crop silages had a slightly higher DM concentration than grass silage. The CP concentration of B silage was numerically lower than that of other silages. Grass silage had a 13–18% higher NDF concentration than whole-crop silages. Due to lower in vitro DMD, the energy content of the WHV silage was 7–8% lower than that of other silages. The addition of hairy vetch to the whole-crop barley (BHV) increased the CP concentration of silage by 25% compared with B silage. Hairy vetch sown with wheat instead of barley resulted in a silage with higher vetch and CP contents. The BHV mixture did not improve the digestibility of silage compared to B silage.

<table>
<thead>
<tr>
<th>Table 1. Chemical composition and calculated feeding values of the experimental feeds (mean±SDa).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silages b</td>
</tr>
<tr>
<td>N, number of samples</td>
</tr>
<tr>
<td>Dry matter (DM), g kg⁻¹ feed</td>
</tr>
<tr>
<td>Organic matter, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Crude protein, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Neutral detergent fibre, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Starch, g kg⁻¹ DM</td>
</tr>
<tr>
<td>in vitro digestibility, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Metabolizable energy, MJ kg⁻¹ DM</td>
</tr>
<tr>
<td>AATc, g kg⁻¹ DM</td>
</tr>
<tr>
<td>PBVd, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Fermentation quality of silages</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Volatile fatty acids, g kg⁻¹ DM</td>
</tr>
<tr>
<td>Lactic+formic acid, g kg⁻¹ DM</td>
</tr>
<tr>
<td>In total N, g kg⁻¹</td>
</tr>
<tr>
<td>Ammonia N</td>
</tr>
<tr>
<td>Soluble N</td>
</tr>
</tbody>
</table>

a Standard deviation.
b G = Grass silage; BHV = Silage made from a mixture of whole-crop barley and hairy vetch; WHV = Silage made from a mixture of whole-crop wheat and hairy vetch; B = Whole-crop barley silage.
c Amino acids absorbed from small intestine.
d Protein balance in the rumen.
Feed intake and diet digestibility

The average feed DM, ME, protein and fibre intakes during the experiment are presented in Table 2. During the experiment the average concentrate proportions of G, BHV, WHV and B diets were 437, 424, 426 and 423 g kg\(^{-1}\) DM, respectively. There were no significant differences in silage DM intake or in the total DMI (kg DM d\(^{-1}\)) between treatments. However, DMI kg\(^{-1}\) W\(^{0.75}\) tended to be 3.5% higher in the B diet than in the G diet. In the WHV diet, energy intake (MJ d\(^{-1}\)) tended to be 4.9% lower than in the G diet, but the BHV and B diets did not differ from the G diet in energy intake. There were no differences in AAT intake between treatments, but CP intake was clearly lower in the BHV and B diets than in the G diet. There was no difference in CP intake between G and WHV diets. In all whole-crop silage diets the NDF intake was significantly lower than that in the G diet (Table 2).

The apparent diet DMD in BHV, WHV and B diets was 5.2, 7.0 and 8.7% lower, respectively, than that of the G diet (Table 2). Diet apparent OM digestibility (OMD) did not differ between G and BHV diets but in WHV and B diets apparent OMD was lower than that in the G diet (Table 2). The apparent CP digestibility was 13.5% lower in the B diet than in the G diet, but BHV and WHV diets did not differ from the G diet in CP digestibility.

Table 2. Daily feed intake and diet digestion.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SEM</th>
<th>p-values of contrasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>N, number of animals</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Duration, d</td>
<td>265</td>
<td>265</td>
</tr>
<tr>
<td>Dry matter (DM) intake, kg DM d(^{-1})</td>
<td>4.41</td>
<td>4.61</td>
</tr>
<tr>
<td>Concentrate</td>
<td>3.42</td>
<td>3.40</td>
</tr>
<tr>
<td>Total intake</td>
<td>7.83</td>
<td>8.01</td>
</tr>
<tr>
<td>Dry matter intake, g kg(^{-1}) W(^{0.75})</td>
<td>81.9</td>
<td>84.0</td>
</tr>
<tr>
<td>Metabolizable energy intake, MJ d(^{-1})</td>
<td>89.6</td>
<td>90.9</td>
</tr>
<tr>
<td>Crude protein intake, g d(^{-1})</td>
<td>1030</td>
<td>946</td>
</tr>
<tr>
<td>AAT d intake, g d(^{-1})</td>
<td>700</td>
<td>703</td>
</tr>
<tr>
<td>Neutral detergent fibre intake, g d(^{-1})</td>
<td>3401</td>
<td>3163</td>
</tr>
<tr>
<td>Apparent diet digestibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry matter</td>
<td>0.733</td>
<td>0.697</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.750</td>
<td>0.723</td>
</tr>
<tr>
<td>Crude protein</td>
<td>0.774</td>
<td>0.745</td>
</tr>
<tr>
<td>Neutral detergent fibre</td>
<td>0.646</td>
<td>0.494</td>
</tr>
</tbody>
</table>

a G = Grass silage; BHV = A mixture of whole-crop barley and hairy vetch; WHV = A mixture of whole-crop wheat and hairy vetch; B = Whole-crop barley.
b Standard error of means.
c Differences between the treatments were compared using an a priori test (Dunnett’s test) so that comparison of the diets was based on the G diet. Contrasts: (1 = G vs. BHV), (2 = G vs. WHV), (3 = G vs. B).
d Amino acids absorbed from small intestine.
e Diet digestibility was determined when the bulls were 503±28 kg live weight, on average. The apparent digestibilities are for the diet and thus are not directly comparable to the \textit{in vitro} digestibilities in Table 1.
In all whole crop diets, apparent NDF digestibility (NDFD) was clearly lower than that in the G diet.

**Gain, carcass characteristics and feed conversion**

The mean final LW of the bulls was 577 kg (Table 3). The final LW of the bulls fed WHV diet tended to be 4.3% lower compared with the bulls fed G diet. The average (all treatments) carcass weight was 299 kg and very close to the pre-planned carcass weight. The carcass weight was 5.6% lower in the WHV diet than in the G diet. The LWG and carcass gain of the bulls was higher with the G diet than with the WHV diet, but BHV and B diets did not differ from the G diet in gain. Treatments had no significant effect on the dressing proportion or carcass conformation (Table 3). The carcass fat score of WHV bulls was 29% lower than that of the G bulls, but the BHV and B diets did not differ from the G diet in carcass fatness.

The feed conversion rate (DM intake kg⁻¹ carcass gain) of the bulls was better and protein conversion (g AAT intake kg⁻¹ carcass gain) tended to be better with the G diet than with the WHV diet. However, there was no significant difference in the energy conversion rate (MJ intake kg⁻¹ carcass gain) between G and WHV diets. BHV and B diets did not differ from the G diet in any feed conversion parameters (Table 3).

### Table 3. Live weight, daily gain, feed conversion rate and slaughter data.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SEM</th>
<th>p-values of contrasts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>G</td>
<td>BHV</td>
<td>WHV</td>
</tr>
<tr>
<td>Initial live weight, kg</td>
<td>320</td>
<td>313</td>
</tr>
<tr>
<td>Final live weight, kg</td>
<td>588</td>
<td>578</td>
</tr>
<tr>
<td>Live weight gain, g d⁻¹</td>
<td>1123</td>
<td>1071</td>
</tr>
<tr>
<td>Carcass gain, g d⁻¹</td>
<td>601</td>
<td>603</td>
</tr>
<tr>
<td>Feed conversion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM intake kg⁻¹ carcass gain</td>
<td>13.12</td>
<td>13.31</td>
</tr>
<tr>
<td>MJ intake kg⁻¹ carcass gain</td>
<td>150</td>
<td>151</td>
</tr>
<tr>
<td>AAT d intake g kg⁻¹ carcass gain</td>
<td>1172</td>
<td>1168</td>
</tr>
<tr>
<td>Slaughter data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carcass weight, kg</td>
<td>303</td>
<td>300</td>
</tr>
<tr>
<td>Dressing proportion, g kg⁻¹</td>
<td>515</td>
<td>519</td>
</tr>
<tr>
<td>EUROP conformation e</td>
<td>3.75</td>
<td>4.83</td>
</tr>
<tr>
<td>EUROP fat classification f</td>
<td>2.75</td>
<td>2.83</td>
</tr>
</tbody>
</table>

**a** G = Grass silage; BHV = Whole-crop barley and hairy vetch mixture; WHV = Whole-crop wheat and hairy vetch mixture; B = Whole-crop barley.

**b** Standard error of means.

**c** Differences between the treatments were compared using an *a priori* test (Dunnett’s test) so that comparison of the diets was based on the G diet. Contrasts: (1 = G vs. BHV), (2 = G vs. WHV), (3 = G vs. B).

**d** Amino acids absorbed from small intestine.

**e** Conformation: (1=poor, 15=excellent).

**f** Fat cover: (1=low, 5 = very high).
Discussion

Diet digestibility and feed intake

In accordance with earlier studies (e.g. Abdalla et al. 1999, Sinclair et al. 2003) and on the stage of grain development, the apparent digestibility of whole-crop cereal-based diets was lower than that of the G diet. In general, the digestibility of whole-crop cereals is highly dependent on the proportion of straw (Sinclair et al. 2003). Based on preliminary results with hairy vetch it can be assumed that the inclusion of hairy vetch in whole-crop silage does not substantially improve the digestibility of the mixture compared with pure cereal crop silage (Lehto 2000). In the present experiment the apparent NDFD of the G diet was clearly higher than that of the whole-crop diets. However, the differences in DMD and OMD between treatments were clearly smaller than the differences in NDFD. This indicates that the starch concentration of whole-crop silages, together with high starch digestibility (reported e.g. by Walsh et al. 2008b) could compensate for the reduced NDFD, which is also suggested by Wallsten (2008). In addition, in the present study grass silage was only of moderate in vitro digestibility which also explains the digestibility results above. If the in vitro digestibility of the grass silage had been greater, the differences in apparent DMD and OMD between treatment levels would presumably have been higher.

In the present experiment, DMI kg\(^{-1}\) W\(^{0.75}\) tended to be higher in the B diet than in the G diet, but there were no significant differences in DMI between other treatments. In general, the DMI of silage can be affected by its DM content, fermentation characteristics, NDF concentration, OMD and NDFD (Huhtanen et al. 2007). While the first two factors can be controlled by wilting and use of appropriate additives at the time of ensiling, the others depend on the maturity stage at harvest and choice of cereal species (Wallsten 2008). According to current practices in Finland, whole-crop cereals are typically harvested at the dough stage with a DM concentration of 30 to 40% (Ahvenjärvi et al. 2006). Within such a range of DM content, active fermentation during the ensiling process is likely to occur, and therefore the preservation of whole-crop silages is based on fermentation using acid-based additives to restrict silage fermentation (Vanhatalo et al. 1999). In the present experiment, all silages were restrictively fermented and of good preservation quality, but due to the wet weather during the harvesting season, the DM content of whole-crop silages (especially BHV) was quite low compared to typical Finnish whole-crop silages and only slightly higher than the DM content of the G diet. This could be one reason for the absence of differences in DMI between BHV, WHV and G treatments.

Digestibility and concentration of the NDF fraction are typically positively and negatively correlated to DMI of the grass silage, respectively (Hetta et al. 2007). However, whole-crop cereal silages differ from grass silage in that the NDF concentration does not increase after heading, but remains constant or even decreases (Crovetto et al. 1998). This difference in maturity-related change between whole-crop cereal silages and grass silage make it difficult to predict the DMI of whole-crop cereal silages from models based on grass silage data (Wallsten et al. 2009). Previous authors have reported that the inclusion of whole-crop silage in grass-silage-based diets has increased forage intake of beef (O’Kiely and Moloney 2002) and dairy (Leaver and Hill 1995, Huhtanen et al. 2007) cattle. Two possible reasons for this are the usually higher DM content and lower NDF concentration of whole-crop silage than those of grass silage (Keady 2005, Ahvenjärvi et al. 2006, Wallsten and Martinsson 2009). However, including whole-crop silage does not always result in higher intake. For example, Ahvenjärvi et al. (2006) reported no increase in DMI when barley silage harvested at the early dough stage was exchanged for grass silage in the diets of dairy cows despite the higher DM content and lower NDF concentration of whole-crop silage compared with grass silage. In the present study, the NDF concentration of the B silage was lowest among silages used, and this may explain the higher DMI (kg W\(^{0.75}\)) in the B diet. Due to higher NDF content of the grass silage, NDF intake was higher in the G diet than in whole-crop diets. Simi-
larly, the differences in CP intake between treatments reflected differences in CP contents of feeds.

**Gain, feed conversion and carcass characteristics**

The absence of any differences between G, BHV and B treatments for LWG or carcass gain was a reflection of the similar ME intakes. In contrast, animal performance (in terms of LWG and carcass gain) for the WHV diet was lower than that for the G diet, primarily because of the lower ME intake with the WHV diet. This was due to a lower in vitro DMD measured with WHV silage. As opposed to energy intake, differences in CP intake between treatments had no effect on performance results in the present study. Similarly, calculations by Titgemeyer and Löest (2001) showed that, while supply of protein and amino acids are a limiting factor with lighter-weight calves offered grass silage, energy availability is the limiting factor with heavier steers.

To our knowledge there are no data available in the literature that were whole-crop-hairy vetch mixtures harvested at a maturity similar to that in this experiment were compared to grass silage-based diets with growing bulls. Some previous studies have reported that the inclusion of whole-crop wheat silage in grass silage-based diets decreased (O'Kiely and Moloney 1999), had no effect (Keady et al. 2007) or increased (O'Kiely and Moloney 2002) the carcass gain of finishing beef cattle. In an Irish study, Walsh et al. (2008b) reported clearly lower animal performances when growing cross-bred steers were fed a grass silage-based diet instead of a fermented whole-crop wheat-based diet. However, grass silage in the study by Walsh et al. (2008b) had a relatively low nutritive value due to the wet weather, late harvesting and relatively poor preservation. Keady (2005) concluded from a review of seven beef cattle studies that inclusion of whole-crop wheat silage in grass silage-based diets did not improve carcass gain of beef cattle. It can be concluded based on the present and on the these earlier experiments that the effects of replacing grass silage by whole-crop silages on the performance of growing cattle differ largely depending on the stage of harvest, cutting height, plant variety and growing conditions that affect the chemical composition and relative proportions of crop components, grain and straw.

The poorer feed conversion rate of animals offered the WHV treatment reflects the magnitude of the decline in carcass gain being proportionally much greater than the scale of decline in total DMI compared to the animals offered G treatment. On the contrary, Walsh et al. (2008b) found a better feed conversion rate with whole-crop wheat compared to grass silage but, as mentioned earlier, grass silage had a relatively low nutritive value then.

In accordance with earlier studies (e.g. Keady et al. 2007, Walsh et al. 2008b), carcass conformation was not affected when grass silage was replaced by whole-crop silages. However, in the WHV diet carcass fat classification decreased by 29% compared to the G diet. According to literature, reducing energy intake usually decreases carcass fat content (e.g. Fishell et al. 1985), which could explain the lower fat classification on the WHV diet. On the other hand, measures of fatness increase also with increasing carcass weight (Keane and Allen 1998) and in our trial, carcass weight was lower in the WHV diet than in the G diet, which probably also explained the differences in fatness. For cattle finished on grass silage and concentrates, Steen and Kilpatrick (2000) concluded that reducing slaughter weights is likely to be a more effective strategy to control carcass fat content than reducing energy intake.

It can be concluded that replacing moderate digestible grass silage with whole-crop wheat and hairy vetch mixture silage decreased the carcass gain and weight of growing dairy bulls due to lower energy intake and poorer feed conversion rate. Instead, replacing moderate digestible grass silage with whole-crop barley or with whole-crop barley and hairy vetch mixture silage resulted in no differences in the performance or carcass characteristics parameters of growing dairy bulls.

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Drying characteristics and kinetics of fluidized bed dried potato

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In developed countries, more than 50% potatoes are consumed as processed products. As drying is the vital phenomenon in processing, it is necessary to investigate the drying characteristics and its kinetics. In this experimental study, drying kinetics of potato in two different shape of cuboidal and cylindrical with three aspect ratio was investigated as a function of drying conditions. Experiments were conducted using air temperatures of 50, 60 and 70 °C, at velocity of 7 ms⁻¹. The experimental moisture data were fitted to Page and Simple models, and a good agreement was observed. The Page model gave better fit than Simple exponential model. In the ranges covered, the values of the effective moisture diffusivity, \(D_{\text{eff}}\) were obtained between 2.278 × 10⁻⁹ to 3.314 × 10⁻⁸ m²s⁻¹ from the Fick’s diffusion model. Using \(D_{\text{eff}}\), the value of activation energy \((E_a)\) was determined assuming the Arrhenius-type temperature relationship.

*Key-words: Cuboidal and cylindrical shape, Aspect ratio, drying kinetics, Page’s and Simple Model

Introduction

The potato (Solanum tuberosum) is an important food crop of the solanaceae family commonly grown for its starchy tuber. It is a grown in about 150 countries throughout the world. India is the third largest country in world in production of potato, after China and Russian Federation. It is produced on an area of 1.4 million hectare having production of 25 million tonnes with productivity 17.86 per hectare in 2006.
Potato is a widely used vegetable in all over the world as food item. Modern food technologists have developed variety of food products which are manufactured from potato. The popular potato products are potato chips, potato powder, potato flakes, potato granules, etc. Potato granules are used for preparation of different variety of crispy food products like namkeen, bhujia, soup curry and snack foods. It can be used for making sweetened food. There are few organised and several private sectors engaged to produce potato granules with other processed food products. The demand is increasing day by day due to population growth and food habit changes by man due to fast life. The new entrepreneur may enter in this field with other types of food and processed items.

Drying is one of the oldest methods of food preservation and it represents a very important aspect of food processing. Hot air drying is the most common method used to preserve the agricultural products in most of the tropical countries. However this technique is extremely weather dependent and has problem of contamination with dust, soil, insects etc. and also drying time required is quite long. The keeping quality of potato slices can be enhanced by drying adequately and with subsequent proper packaging.

The cost of dried product depends on the drying process. Therefore it is necessary to dry the product with minimum cost, energy and time. Fluidized bed drying, due to intensive heat and mass transfer between the drying air and particles being dried, results in shortening of the drying time. Among various drying methods, fluidized bed drying is very convenient method for heat sensitive food materials as it prevents these products from overheating due to uniform heat transfer quality (Giner and Cavelo 1987). The drying of vegetables in a fluidized bed dryer produces dry vegetable pieces of excellent quality in a much shorter time than in continuous belt dryers (Bobic 2002).

Though, there is a lot of work done on the drying of fruits and vegetables, but the information is scanty on the drying kinetics of vegetables particularly on potato. Therefore the present investigation was undertaken to study the effect of product shape on drying kinetics of potato particulates, to study the drying behaviour with the help of models and to estimate the Arrhenius activation energy during potato drying.

Material and methods

The fluidized bed drying of potato particulates were investigated in fluidized bed dryer installed in the Department of Processing and Food Engineering, College of Technology and Engineering, MPUAT, Udaipur. The table top fluidized bed dryer as shown in Figure 1 (Make Sherwood Scientific Ltd. Cambridge, England) was used in present study. The dryer consists of centrifugal blower to supply air, an electric heater and an air filter. The air temperature was controlled by means of proportional controller. An air flow rate of 7 m s⁻¹ as measured with an anemometer, was used during the experiments. The samples were dried in the perforated cylindrical...
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chamber. The air was circulated by variable speed blower and heated by electricity. Potatoes procured from the local market were used in the studies. At the start of each experiment, potatoes were washed under tap water, peeled and cut into cuboidal with aspect ratio (area:length, A:L ratio) of 1:1 (5 mm × 5 mm × 5 mm), 1:2 (5 mm × 5 mm × 10 mm) and 1:3 (5 mm × 5 mm × 15 mm) and cylindrical shape with aspect ratio (diameter:length, D:L ratio) as 1:1 (5 mm × 5 mm), 1:2 (5 mm × 10 mm) and 1:3 (5 mm × 15 mm) using sharp stainless steel knife. Three batches of potatoes were prepared for each shape (cuboidal and cylindrical) and each ratio (1:1, 1:2, 1:3). Three drying temperatures such as 50 °C, 60 °C and 70 °C were used at 7 ms⁻¹ air velocity.

The potato samples were immersed, immediately after cutting in a sodium metabisulphite solution (0.1% w/w) for 15 min to prevent browning which may otherwise take place during drying. After that, cut potatoes were drained on a mesh tray and kept in a cold room at 4 °C for 24 h to equilibrate the moisture content.

The initial moisture content of potatoes was determined by using vacuum oven according to AOAC (1995) method. The 10 g potato particulates were weighted with an electric balance (±0.001 g), for moisture determination and kept in the vacuum oven at 70 °C and 13.3 kPa. After that potato particulates were transferred from the vacuum oven to the desiccators (containing silica) to cool. Moisture content was determined as the loss in weight of the potato particulates. The drying of potato particulates were finalized when the moisture content decreased to 6% from an initial value of 80.7% wet basis (wb) (400% dry basis). The product was cooled for 10 minutes after drying and kept in air glass jars.

**Modeling**

The Simple model and Page’s model were used to investigate the effect of shapes and their aspect ratio on drying characteristic of food. The basic model is known as the Simple model and is as follows

\[
MR = e^{-kt}
\]  

(1)

where,

- **MR** = Moisture ratio
- **k** = drying constant for Simple model
- **t** = time

The Page model is applied to overcome the shortcomings of a Simple model, with an empirical modification to the time term by introducing an exponent ‘n’ (Madamba et al. 1996).

\[
MR = e^{(-kp^ne)}
\]

(2)

where,

- **kp** = drying constant for Page model.

The moisture and vapour migration during drying period is controlled by diffusion. The rate of moisture movement is described by an effective diffusivity. Fick’s second law of diffusion is used to describe a moisture diffusion process.

The diffusion equation of potato particulates for cuboidal shape

\[
MR = \frac{M - M_0}{M_e - M_0} = \sum_{n=0}^{\infty} \frac{4}{\pi^2 n^2} \exp \left[ -\frac{n^2 \pi^2 D_{eff}}{L^2} \right] e^{-\frac{1}{(2n-1)^2}}
\]

(3)

The diffusion equation of potato particulates for cylindrical shape

\[
MR = \left( \frac{M - M_e}{M - M_0} \right) = \sum_{n=0}^{\infty} \frac{1}{\pi^2 n^2} \exp \left[ -\frac{n^2 \pi^2 D_{eff}}{L^2} \right] e^{-\frac{1}{(2n-1)^2}}
\]

(4)

where,

- **MR** = Moisture ratio
- **M** = Final moisture content (% db)
- **M_0** = Initial moisture content (% db)
- **M_e** = Equilibrium moisture content (% db)
- **β** = Roots of Bessel moisture content
- **D_{eff}** = Diffusion function (m²s⁻¹)
- **L** = Slab thickness (mm)
- **n** = Positive integer
A general form of equation can be written in logarithmic form

\[ \ln MR = A - Bt \]  

(5)

where,

- \( A \) = constant
- \( B \) = constant is \( \Pi^2D_{eff}L^{-2} \) for cuboidal and \( \beta^{2}D_{eff}r^{-2} \) for cylindrical shape.

The dependence of drying constants for Simple (\( k_s \)) and Page’s (\( k_p \)) model of the two models was evaluated, using Arrhenius type equation as given below

\[ K = K_0 \exp \left( -\frac{E_a}{RT} \right) \]  

(6)

where,

- \( K \) = Drying constant, h\(^{-1}\)
- \( K_0 \) = Reference value of drying constant, h\(^{-1}\)
- \( E_a \) = Energy activation, kJ mol\(^{-1}\)
- \( R \) = Universal gas constant, J mol\(^{-1}\)K\(^{-1}\)
- \( T \) = Absolute temperature, K

Parameters \( k_0 \) and \( E_a \) were estimated using drying constant and its reference value, respectively.

### Results and discussion

#### Drying Curves

The drying times according to the experimental conditions selected are presented in Table 1. The drying curves of moisture content versus drying time for drying of potato cuboidal and cylindrical particulates for aspect ratio 1:1 at temperatures (50°C, 60°C and 70°C) were presented in Figure 2 and 3. Similar trend was found for other aspect ratios of cuboidal as well as cylindrical shape of potato particulates.

In general, time required to reduce moisture content to any given level was dependant on drying conditions being highest, 1.66 h at 50°C and lowest 1.5 h at 70°C irrespective of product shape and its aspect ratio. It was observed, for cuboidal shape of potato, that when aspect ratio increased from 1:1 to 1:3 at given air temperature, the drying time also increased. A similar trend for increase in drying time was also observed for cylindrical shaped potato. The effect of shape on drying time was not significant as per the ANOVA carried out.

### Table 1. Observations of drying conditions and drying time

<table>
<thead>
<tr>
<th>Cuboidal shape</th>
<th>Cylindrical shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>Drying time (h)</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td><strong>A:L</strong> (^1)</td>
<td></td>
</tr>
<tr>
<td>1:1</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>1.63</td>
</tr>
<tr>
<td>70</td>
<td>1.5</td>
</tr>
<tr>
<td>1:2</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>1.65</td>
</tr>
<tr>
<td>70</td>
<td>1.5</td>
</tr>
<tr>
<td>1:3</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>1.68</td>
</tr>
<tr>
<td>70</td>
<td>1.51</td>
</tr>
</tbody>
</table>

\(^1\)Aspect ratio A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

\(^2\)Aspect ratio D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.
The drying curves of moisture ratio versus drying time for drying of potato cuboidal and cylindrical particulates for aspect ratio 1:1 at temperatures (50 °C, 60 °C, and 70 °C) were presented in Figure 4 and 5. From the plot of MR versus drying time gives straight line with negative slope. The slope became steeper with increase in drying air temperature.

**Moisture diffusivity and activation energy**

The variation in moisture diffusivity with moisture content is a complex and system specific function. The effective moisture diffusivity ($D_{eff}$) of a food material characterizes its intrinsic mass transport property of moisture which includes molecular diffusion, liquid diffusion, vapour diffusion, hydrodynamic flow and other possible transport mechanisms (Crank 1975). The moisture loss data during fluidized bed drying were analyzed and moisture ratio at every 15 minute interval was calculated. From the plot of MR versus drying time gives straight line with negative slope. The slope became steeper with increase in drying air temperature. Moisture diffusivities were calculated from the slopes of these straight lines using Eq. 3 and 4. The coefficient of determination and moisture diffusivities evaluated for various process conditions are given in Table 3.
Bakal, S. et al. Drying characteristics and kinetics of potato

For cuboidal shape of potato having A:L 1:1, the moisture diffusivity increased from $2.27 \times 10^{-9}$ to $3.165 \times 10^{-9}$ m$^2$s$^{-1}$ as the drying air temperature increased from 50 °C to 70 °C. Similar values of moisture diffusivities have been reported by some researchers for the food products (Madamba et al. 1996, Pinthus et al. 1997, Senadeera et al. 2003, McMinn et al. 2003, Odilio et al. 2004, Charles et al. 2005). For all aspect ratios of cuboidal potato, moisture diffusivity increased with increase in temperature. This is because the product temperature increased with increased in drying air temperature and moisture diffusion is an internal process which very much depends on product temperature (Singh and Heldman 2004).

ANOVA was carried on to study the effect of temperature and shape on moisture diffusivity. It was inferred from the ANOVA that shape and temperature had significant effect on moisture diffusivity at 5% level of confidence.

Moisture diffusivities were calculated from the slopes of these straight lines using Eq. 3 and 4. The coefficient of determination and moisture diffusivities evaluated for various process conditions are given in Table 3. The activation energy from moisture diffusivity of the drying data was calculated, using Arrhenius type Eq. 6 with replacement of the Reference value of drying constant $k_0$ with coefficient of diffusivity ($D_0$) and their values were presented in Table 4.

### Table 2. Regression analysis for constants and coefficients for simple and Page model.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Temperature (°C)</th>
<th>Simple model</th>
<th>Page model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_s$ (h$^{-1}$)</td>
<td>$R^2$</td>
<td>MAE (%)</td>
</tr>
<tr>
<td>Cuboidal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A:L = 1:1</td>
<td>50</td>
<td>0.818</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.331</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.631</td>
<td>0.98</td>
</tr>
<tr>
<td>A:L = 1:2</td>
<td>50</td>
<td>1.702</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.139</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.612</td>
<td>0.98</td>
</tr>
<tr>
<td>A:L = 1:3</td>
<td>50</td>
<td>1.640</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.083</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.611</td>
<td>0.99</td>
</tr>
<tr>
<td>Cylindrical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D:L = 1:1</td>
<td>50</td>
<td>2.035</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.340</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.600</td>
<td>0.99</td>
</tr>
<tr>
<td>D:L = 1:2</td>
<td>50</td>
<td>1.745</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.230</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.729</td>
<td>0.97</td>
</tr>
<tr>
<td>D:L = 1:3</td>
<td>50</td>
<td>1.689</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.201</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.610</td>
<td>0.98</td>
</tr>
</tbody>
</table>

$k_s$ = drying constant for Simple model, $k_p$ = drying constant for Page’s model, MAE = Mean absolute error temperature, $n$ = constant.

1 $A:L$ = area: length ratio, 1:1 = 5 mm × 5 mm × 5 mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

2 $D:L$ = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.

Modeling of drying behaviour of potato

In order to determine the moisture content as function of drying time, a Simple and Page model using Marquardt method of non-linear regression procedure in SY-Stat were initially fitted. For adequacy of model fit, coefficient of determination
Table 3. Effective diffusivity and regression coefficient values

<table>
<thead>
<tr>
<th>Shape</th>
<th>Drying temperature (°C)</th>
<th>Regression equation</th>
<th>Moisture diffusivity (m²s⁻¹)</th>
<th>Coefficient of Determination R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuboidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A:L¹ = 1:1</td>
<td>50</td>
<td>y = -0.0036x + 0.014</td>
<td>2.777 × 10⁻⁹</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>y = -0.0043x + 0.013</td>
<td>2.721 × 10⁻⁹</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>y = -0.005x + 0.020</td>
<td>3.165 × 10⁻⁹</td>
<td>0.99</td>
</tr>
<tr>
<td>A:L = 1:2</td>
<td>50</td>
<td>y = -0.0034x + 0.016</td>
<td>5.612 × 10⁻⁹</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>y = -0.0040x + 0.027</td>
<td>1.013 × 10⁻⁹</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>y = -0.0052x + 0.028</td>
<td>1.317 × 10⁻⁹</td>
<td>0.99</td>
</tr>
<tr>
<td>A:L = 1:3</td>
<td>50</td>
<td>y = -0.0032x + 0.01</td>
<td>1.824 × 10⁻⁹</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>y = -0.0041x + 0.019</td>
<td>2.337 × 10⁻⁹</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>y = -0.0055x + 0.035</td>
<td>3.314 × 10⁻⁹</td>
<td>0.98</td>
</tr>
</tbody>
</table>

| Cylindrical |                         |                     |                               |                                 |
|             | D:L² = 1:1              |                     |                               |                                 |
|             | 50                     | y = -0.0036x + 0.71  | 2.777 × 10⁻⁹                 | 0.99                            |
|             | 60                     | y = -0.0047x + 0.070| 2.295 × 10⁻⁹                 | 0.99                            |
|             | 70                     | y = -0.005x + 0.042 | 3.418 × 10⁻⁹                 | 0.97                            |
|             | D:L = 1:2               |                     |                               |                                 |
|             | 50                     | y = -0.0033x + 0.016| 5.358 × 10⁻⁹                 | 0.98                            |
|             | 60                     | y = -0.0044x + 0.014| 1.114 × 10⁻⁹                 | 0.99                            |
|             | 70                     | y = -0.0050x + 0.013| 1.266 × 10⁻⁹                 | 0.97                            |
|             | D:L = 1:3               |                     |                               |                                 |
|             | 50                     | y = -0.0033x + 0.016| 1.880 × 10⁻⁹                 | 0.99                            |
|             | 60                     | y = -0.0041x + 0.015| 2.336 × 10⁻⁹                 | 0.99                            |
|             | 70                     | y = -0.0044x + 0.036| 2.507 × 10⁻⁹                 | 0.99                            |

y = ln MR, dimensionless; x = drying air temperature, °C; MR = Moisture ratio.

¹A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5 mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.
²D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm and 1:3 = 5 mm × 15 mm.

Table 4. Activation Energy (Eₐ) for different shapes of potato particulates drying using Experimental data and the values from model

<table>
<thead>
<tr>
<th>Shape</th>
<th>Aspect Ratio</th>
<th>Experimental value</th>
<th>Simple model</th>
<th>Page’s model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D₀ × 10⁻⁹</td>
<td>Eₐ kJ mol⁻¹</td>
<td>k₀ kJ mol⁻¹</td>
<td>k₀ kJ mol⁻¹</td>
</tr>
<tr>
<td></td>
<td>A:L = 1:2</td>
<td>2.32</td>
<td>19.95</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>A:L = 1:3</td>
<td>2.36</td>
<td>18.96</td>
<td>490</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>D:L² = 1:1</td>
<td>2.25</td>
<td>22.36</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td>D:L = 1:2</td>
<td>2.23</td>
<td>20.60</td>
<td>443</td>
</tr>
<tr>
<td></td>
<td>D:L = 1:3</td>
<td>2.28</td>
<td>16.04</td>
<td>460</td>
</tr>
</tbody>
</table>

D₀ = Coefficient of diffusion; k₀ = Reference value of drying constant; Eₐ = Energy activation.

¹A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5 mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.
²D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm and 1:3 = 5 mm × 15 mm.
(R²) and mean absolute error percentage (MAE, %) (Noomborn and Verma 1986, Palipane and Driscoll 1994, Madamba et al. 1996) were calculated and presented in Table 2. The MR versus drying time was plotted as shown in Figure 6 and 7.

The drying constant in Simple (kₛ) and Page model (kₚ) increased with increase in drying temperature for all aspect ratios. The kₛ increased from 0.818 to 2.631 h⁻¹ as air temperature increased from 50 to 70 °C for cuboidal shaped potato (A:L 1:1). The kₚ increased from 2.092 to 2.923 h⁻¹, in case of cylindrical shaped (D:L 1:1) potato for same increase in temperature. Similar results were found for all A:L as well as D:L ratios. For both Simple and Page models, the highest value of drying constant kₛ and kₚ were observed as 2.923 h⁻¹ and 2.729 h⁻¹. The ANOVA carried out to study the effect of temperature of drying air on drying constant showed that temperature had more pronounced effect on Page model. The value of ‘n’ in the Page model was non significant (p > 0.05) with the temperature for cuboidal as well as cylindrical shape. Page model gave better fit than Simple model, when the values of R² and MAE compared.

The activation energy of the two models was calculated, using Arrhenius type Eq. 6 and their values were presented in Table 4. It was observed that the activation energy decreases with increases in AR for cuboidal as well as cylindrical shape.

Activation energy values estimated from diffusivity data were very close to activation energy values from drying kinetics data.

**Conclusions**

The effects of product shape on drying of potato particulates for fluidized bed drying were studied. The moisture content in potato decreased with increase in drying air temperature. Also when aspect ratio increased from 1:1 to 1:3 at given air temperature, the drying time increased for both cuboidal as well as for cylindrical shape of potato. The moisture diffusivity coefficient of potato particulates was in the range of \(2.278 \times 10^{-9}\) to \(3.314 \times 10^{-8}\) m²s⁻¹. The moisture diffusion coefficient increased with increase in thickness of sample. Page model gave better fit than Simple model for the fluidized bed drying conditions under study. Activation energy values estimated from diffusivity data were very close to activation energy values from drying kinetics data.
References


The effect of processing on the amino acid content in green cauliflower

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The aim of the work was to evaluate the level of amino acids and quality of protein in fresh green cauliflower and in three kinds of products as eaten: fresh cauliflower after cooking; and two types of frozen product: frozen cauliflower obtained using the traditional method (blanching-freezing-frozen storage-cooking); and by the modified method (cooking-frozen storage-defrosting-heating in a microwave oven). Frozen products were stored for 12 months at −20 °C. Fresh inflorescences contained 24.32 g amino acids in 1 kg of edible parts. Expressed as g per 16 g N the content was 86.59 g, with essential amino acids constituting 44%. Culinary processing and the freezing process did not result in a drastic decrease in amino acid content apart from tyrosine. For all the samples the limiting amino acids of the first order was cystine with methionine and of the second order leucine.

Key-words: green cauliflower, amino acids, blanching, cooking, freezing, culinary treatment

Introduction

In the countries of the European Union, cauliflower occupies an important position in the production of fresh and frozen vegetables (FAOSTAT 2008). In the late 1980s the cultivation of cauliflower with green florets was introduced in the countries of Western Europe (Vanparys 1999), and a decade later in Poland (Gajewski and Radzanowska 2003). In an investigation carried out by Gębczyński and Kmiecik (2007) green cauliflower was found to contain more dry matter, vitamin C, total carotenoids, beta carotene, and polyphenols than white florets; its antioxidative activity was higher; it was a good source of mineral compounds (Kmiećik et al. 2007); it did not accumulate either lead or cadmium (Lisiewska et al. 2007); and its chlorophyll content was only 15% lower than that in broccoli florets (Kmiećik et al. 2008a). Compared with white cauliflower, the raw material with green
inflorescences shows better storage performance (Gajewski and Radzanowska 2003) and is a more attractive material for the freezing industry since in the sensory evaluation frozen green cauliflower products achieved higher scores for colour and smell (Gębczyński and Kmiecik 2007).

Nowadays, consumers expect to obtain food products which are easy to prepare, described as “do-it-for-me” or “ready-to-eat” (Sloan 2004). Fast and simple preparation of food has been made possible by the widespread use of microwave ovens, both in the catering industry and in homes (Datta et al. 2005). The introduction to the market of this easily prepared attractive vegetable with high nutritional content increases the range of products available. Frozen green cauliflower can improve the diet of vegans since one third of its dry matter is made up of protein compounds (Souci et al. 2000).

The aim of the work was to evaluate changes in amino acid content and in the quality of protein in green cauliflower florets cooked from fresh, as well as prepared for consumption after freezing and frozen storage: obtained using the traditional technology (raw material-blanching-freezing-frozen storage-cooking in brine) and the other obtained using the modified technology (raw material-cooking in brine-freezing-frozen storage-defrosting and heating in a microwave oven), resulting in a convenience food product.

Production of frozen products

The preparation for freezing. Two variants were used in preparing the raw material for freezing. Using traditional technology (variant I) the raw material was blanched, and after freezing and refrigerated storage the frozen cauliflower needed traditional cooking. In variant II the raw material was cooked before freezing to a condition approximating to consumption consistency, hence the obtained do-it-for-me product merely required defrosting and heating in a microwave oven.

In variant I cauliflower florets were blanched in a stainless steel vessel in water, the proportion of the blanched material to water being 1:5 (w/w). The blanching temperature was 95–98 °C and the time was 3 min. and 15 s. These conditions permitted a decrease in the activity of catalase and peroxidase to a level below 5% of the initial value. After blanching the material was immediately cooled in cold water, slightly shaken and left for 30 min on sieves to drain the water remaining on the surface.

In variant II cauliflower florets were cooked in 2% brine to a condition approximating to consumption consistency. The cooking was carried out in a stainless steel vessel and the proportion of the raw material to brine was 1:1 (w/w). The cauliflower was placed in boiling water. The time of cooking measured from the moment when the medium began boiling again, to the moment the desired consistency was obtained was 6 min. After cooking the florets were drained, placed on sieves and cooled in a stream of cold air.

The material from the blanched and cooked samples was placed on trays and frozen at –40 °C representing the whole batch of the vegetable was taken for evaluation of raw material and of cooked material to consumption consistency in 2% brine. The cooking was carried out in a stainless steel vessel and the proportion of the raw material to brine was 1:1 weight/weight (w/w). The remaining part was divided in half; each half being processed using a different technology.

Material and methods

The investigated material consisted of green cauliflower, Trevi F₁ cultivars. The evaluation concerned raw cauliflower, cooked in 2% brine and two types of frozen cauliflower prepared for consumption after 12 months of refrigerated storage at –20 °C.

The cauliflower was grown in the experimental field of the research unit, where technological experiment was conducted, and harvested at the beginning of October. Well formed cauliflower heads were separated from stalks and divided into florets about 5 cm in diameter, their stalks being cut 2 cm below the lowest ramification. A mean sample
to −20 °C in a Feutron blast freezer, type 3626-51, which was obtained inside the frozen product after 90 min. After the desired temperature was obtained, 500 g portions of the cauliflower were packed in polyethylene bags suitable for the storage of refrigerated products. The bags were placed in chamber freezer at −20 °C.

The preparation of frozen cauliflower for evaluation. Frozen cauliflower blanched before freezing was cooked in 2% brine, the proportion in weight of brine to cauliflower being 1:1 (w/w). As in the case of cooking, the material was put in boiling water. The time of cooking was 5 min measured from the moment when the brine was boiling again. After cooking the water was immediately drained and the product was cooled to 20 °C for analyses of chemical composition.

Frozen cauliflower cooked before freezing was defrosted and a portion of 500 g in a heat-resisting vessel covered with a lid was heated in a Panasonic microwave type NN-F621. The time of defrosting and heating to 75 °C was 7 min 45 sec (Codex Alimentarius 1993).

Analytical procedures

The content of dry matter was determined by gravimetric method as the mass loss of the sample at 96–98 °C according to method 32.064 and total nitrogen (N) according to method 2.057 described by the AOAC (1984). The content of amino acids was determined using an AAA-400 amino acid analyzer (INGOS, the Czech Republic). The analytical procedure applied was in accordance with the recommendations of the producer. The freeze-dried material was hydrolyzed in 6 M HCl for 24 h at 110 °C. After cooling, filtering and washing, the hydrolyte was evaporated in a vacuum evaporator at temperature below 50 °C for sulfur-containing amino acids and below 60 °C for other amino acids, the dry residue being dissolved in a buffer of pH 2.2. The prepared sample was analysed using the ninhydrine method. Buffers of pH 2.6, 3.0, 4.25, and 7.9 were applied. The ninhydrine solution was buffered at pH 5.5. A column 370 mm in length was filled with Ostion ANB INGOS ionex (the Czech Republic). The temperature of the column was 55–74 °C; that of the reactor 120 °C. The determination of the sulfur-containing amino acids, methionine and cystine, was carried out by means of oxygenating hydrolysis, using a mixture of formic acid and hydrogen peroxide (9:1) at 110 °C for 24 h. After cooling, the sample was processed as with acid hydrolysis. Buffers of pH 2.6 and 3.0 were used; the temperature of the column was 60 °C and that of the reactor 120 °C. The calculations were carried out according to the external standard.

Each experiment was carried out in two replications (samples). All determinations were carried out in two replications for each experiment.

Expression of results

The level of amino acids was given in 1 kg of edible portion of the products in order to compare the amino acid content in green cauliflower according to the culinary and technological processing applied. The composition of amino acids was also expressed as grams per 16 g of N to estimate the quality of the protein in cauliflower by comparing it with the FAO/WHO (1991) pattern. On the basis of the amino acid composition, the chemical score index (CS) was calculated using the Mitchell and Block method (Osborne and Voogt 1978), and the integrated essential amino acids index (EAA) using the Oser (1951) method.

Statistical analysis

Statistical analysis allowing a comparison of the content of amino acids in the raw material, cooked material and frozen cauliflower after storage and preparation for consumption was carried out using single-factor analysis of variance (ANOVA) on the basis of the Duncan test, and the least significant difference (LSD) was calculated at the probability level α=0.05 (Snedecor and Cochran 1980). The Stastica 6.1 programme was applied.
Results and discussion

In 1 kg of edible parts of raw green cauliflower, the total content of amino acids was 24.32 g of which essential amino acids constituted 44% (Table 1). No data were found in the literature concerning the content of amino acids in green cauliflower, hence the point of reference was white cauliflower and broccoli. Eppendorfer and Bille (1996) reported that in white cauliflower the percentage of essential amino acids in their total content was 37–48%, depending on nitrogen fertilization. According to Kmiecik et al. (2009) in broccoli florets this indica-

Table 1. Amino acid composition of raw and as eaten green cauliflower, g kg⁻¹ of edible portion.

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Raw material</th>
<th>Cooked from raw material</th>
<th>Prepared from frozen and stored material</th>
<th>Blanched before freezing</th>
<th>Cooked before freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoleucine</td>
<td>1.02±0.14</td>
<td>1.06±0.19</td>
<td>1.11±0.15</td>
<td>1.15±0.15</td>
<td></td>
</tr>
<tr>
<td>Leucine</td>
<td>1.74±0.15</td>
<td>1.84±0.24</td>
<td>1.91±0.27</td>
<td>2.04±0.30</td>
<td></td>
</tr>
<tr>
<td>Lysine</td>
<td>1.75±0.21</td>
<td>1.86±0.23</td>
<td>1.90±0.29</td>
<td>2.02±0.30</td>
<td></td>
</tr>
<tr>
<td>Cystine</td>
<td>0.27±0.09</td>
<td>0.26±0.09</td>
<td>0.25±0.08</td>
<td>0.30±0.09</td>
<td></td>
</tr>
<tr>
<td>Methionine</td>
<td>0.32±0.11</td>
<td>0.30±0.08</td>
<td>0.28±0.09</td>
<td>0.31±0.10</td>
<td></td>
</tr>
<tr>
<td>Total sulphur amino acids</td>
<td>0.59±0.21</td>
<td>0.56±0.18</td>
<td>0.53±0.15</td>
<td>0.61±0.19</td>
<td></td>
</tr>
<tr>
<td>Tyrosine</td>
<td>1.41±0.24</td>
<td>0.94±0.16</td>
<td>0.81±0.18</td>
<td>1.04±0.24</td>
<td></td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>1.05±0.13</td>
<td>1.10±0.10</td>
<td>1.11±0.17</td>
<td>1.21±0.15</td>
<td></td>
</tr>
<tr>
<td>Total aromatic amino acids</td>
<td>2.46±0.37</td>
<td>2.04±0.25</td>
<td>1.92±0.35</td>
<td>2.25±0.39</td>
<td></td>
</tr>
<tr>
<td>Threonine</td>
<td>1.03±0.15</td>
<td>1.06±0.19</td>
<td>1.10±0.16</td>
<td>1.16±0.15</td>
<td></td>
</tr>
<tr>
<td>Valine</td>
<td>1.43±0.20</td>
<td>1.45±0.20</td>
<td>1.49±0.26</td>
<td>1.58±0.24</td>
<td></td>
</tr>
<tr>
<td>Histidine</td>
<td>0.78±0.18</td>
<td>0.82±0.16</td>
<td>0.85±0.20</td>
<td>0.88±0.19</td>
<td></td>
</tr>
<tr>
<td>Total essential amino acids</td>
<td>10.8±1.59</td>
<td>10.7±1.54</td>
<td>10.8±1.74</td>
<td>11.7±1.85</td>
<td></td>
</tr>
<tr>
<td>Arginine</td>
<td>1.52±0.20</td>
<td>1.61±0.22</td>
<td>1.63±0.24</td>
<td>1.76±0.24</td>
<td></td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>2.61±0.37</td>
<td>2.74±0.25</td>
<td>2.71±0.22</td>
<td>2.95±0.27</td>
<td></td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>4.26±0.35</td>
<td>4.46±0.38</td>
<td>4.10±0.17</td>
<td>4.64±0.19</td>
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</tr>
<tr>
<td>Serine</td>
<td>1.18±0.21</td>
<td>1.25±0.17</td>
<td>1.27±0.18</td>
<td>1.34±0.19</td>
<td></td>
</tr>
<tr>
<td>Proline</td>
<td>1.43±0.23</td>
<td>1.54±0.14</td>
<td>1.57±0.23</td>
<td>1.69±0.28</td>
<td></td>
</tr>
<tr>
<td>Glycine</td>
<td>1.16±0.19</td>
<td>1.17±0.14</td>
<td>1.19±0.16</td>
<td>1.28±0.16</td>
<td></td>
</tr>
<tr>
<td>Alanine</td>
<td>1.36±0.11</td>
<td>1.28±0.17</td>
<td>1.29±0.13</td>
<td>1.39±0.19</td>
<td></td>
</tr>
<tr>
<td>Total non-essential amino acids</td>
<td>13.5±1.59</td>
<td>14.1±1.14</td>
<td>13.7±1.33</td>
<td>15.1±1.49</td>
<td></td>
</tr>
<tr>
<td>Total amino acids</td>
<td>24.3±3.13</td>
<td>24.7±2.59</td>
<td>24.6±3.04</td>
<td>26.7±3.32</td>
<td></td>
</tr>
<tr>
<td>Dry matter, g kg⁻¹ of edible portion</td>
<td>93.0</td>
<td>104.6</td>
<td>92.6</td>
<td>111.3</td>
<td></td>
</tr>
<tr>
<td>Total N, g kg⁻¹ dry matter</td>
<td>48.3</td>
<td>47.7</td>
<td>50.6</td>
<td>48.6</td>
<td></td>
</tr>
</tbody>
</table>

The data reported are means of two independent replicate analyses, each from two samples. Means in the same raw with different letters are significantly different at p < 0.05. Means in the same raw without letters are not significantly different at p < 0.05.
Amino acids in green cauliflower

The cooking of fresh cauliflower did not cause significant changes in amino acid levels compared with the raw material except for tyrosine, whose content was considerably (33%) and significantly lower. In the remaining amino acids the recorded differences varied in the range of –6% – +8%. The as-eaten products obtained from frozen cauliflower also differed from the raw material only in having significantly lower tyrosine content. Apart from the content of tyrosine, the percentage differences for cooked frozen product obtained using the traditional method ranged from –12% to +10% and for frozen product obtained using the modified method from –3% to +18%. In edible parts of the latter product, the content of individual amino acids was 4–28% higher than in the traditional frozen product. However, after calculating the results in dry matter, the highest content of all amino acids except tyrosine was in the frozen product obtained using the traditional technology, while the lowest content of most amino acids was found in the product obtained from fresh cauliflower.

According to Ziena et al. (1991), changes in amino acid content could be affected by protein solubility in water and the destruction of the skin surface. It is possible that these changes were relative since other water-soluble compounds could also be leached, among them sugars, acids, mineral constituents and vitamins (Lisiewska et al. 2003, Słupski et al. 2004, Kmiecik et al. 2007). Changes in dry matter content (Table 1) give an indication of the extent of the above changes. For the cooked fresh cauliflower dry matter was 12% higher; for the product obtained from traditionally frozen cauliflower it was similar; and for the product obtained using the modified method it was 20% higher. This pronounced increase in dry matter content for products obtained with the use of microwave ovens has already been reported in the literature (Gębczyński 2006, Gębczyński and Lisiewska 2006).

Murcia et al. (2001) found that prolonging the time of thermal preliminary processing in water increased the loss of amino acids owing to thermal degradation. In the present investigation, thermal operations were halted, in the case of cauliflower frozen after blanching, when enzymatic activity had been sufficiently reduced and, in the case of cauliflower frozen after cooking, when, according to the sensory evaluation, consumption consistency had been achieved. The quantity of water used was also limited to the absolute minimum. Diasolua-Ngudi et al. (2003) showed that losses increased with the quantity of water used as a result of diffusion. The present authors agree that changes in the level of amino acids are not only determined by the pre-treatment parameters but also by the species in question and the edible parts of the vegetable, i.e. the particular tissue under investigation (Klein and Mondy 1981, Murcia et al. 2001, Kmiecik et al. 2008b, Kmiecik et al. 2009, Lisiewska et al. 2008). The literature shows that the retention of amino acids varies depending on the factors mentioned above: statistically significant losses may be found (Candela et al. 1997, Diasolua-Ngudi et al. 2003); but also, as in the present investigation, no significant changes might be observed (Khalil and Mansour 1995, Murcia et al. 2001, El-Adawy 2002, Korus et al. 2003, Lisiewska et al. 2004); or, as reported by Mutia and Uchida (1993), the content of amino acids in edible parts may increase significantly.

The investigated samples of cauliflower were characterised by similar amounts of amino acids expressed as g per 16 g N. Only in the case of tyrosine was a significantly lower level found in the protein of products as eaten compared with the protein in fresh cauliflower, no statistical differences being noted between the as-eaten samples. Despite the lack of statistical differences, in 16 g N of cooked fresh cauliflower the content of individual amino acids was 3–15% lower than in 16 g N of raw cauliflower; in 16 g N of the product from the traditionally frozen cauliflower the chang-
es varied from -16% to +6%; and in 16 g N of the product from the cauliflower frozen using the modified method the content was 3–19% lower. In the case of tyrosine the respective losses were 40%, 44% and 38%. Candela et al. (1997) showed more than a 50% loss of tyrosine in kidney bean during thermal processing in water. The as-eaten product which had the highest content of most amino acids was that obtained from traditionally frozen cauliflower.

During the preparation of food the side chains of some protein-bound amino acids can react chemically with each other or with other molecules present in the food (Sherr et al. 1989). Klein and Mondy (1981) deduced that heat treatments may lead to compositional changes in nitrogenous compounds depending on the mechanism of heat transfer and the particular tissue under treatment. Baxter (1995) used amino acid standards to study their behaviour in heat processes. This author showed that after treatment the level of all the amino acids was 8–14% lower except for lysine, which showed a loss of 28%. In the Maillard process, which is possibly the most frequent cause of amino acid loss, the initial reaction involving sugars and amino acids is reversible. However, subsequent reactions are not reversible and amino acids are destroyed (Baxter 1995).

In the as-eaten products under investigation, the content of nitrogen changed slightly compared with the raw material. According to Lanfermeijer et al. (1989), changes in the content of nitrogen compounds due to thermal processing can be affected by their solubility in water and by possible damage to the outer tissue. It has also been claimed that the decomposition of some protein fractions rich in amino acids results in higher values of other amino acids when they are calculated on the basis of 16 g N (Mutia and Uchida 1993).

A comparison of essential amino acid content in the investigated samples of green cauliflower with the FAO/WHO (1991) standard showed that in all the samples the limiting amino acids of the first order were sulfuric amino acids and of the second order leucine; for these amino acids the value of the CS index was 72–84 and 89–99 respectively (Table 2). Cooking fresh vegetable and preparing frozen products for consumption after 12-months’ storage brought about a similar decrease in the nutritional value of protein expressed by the value of the CS index for sulfuric amino acids, as well as variations in the level of this indicator for the

<table>
<thead>
<tr>
<th>Index</th>
<th>Amino acid</th>
<th>Raw material</th>
<th>Cooked from raw material</th>
<th>Prepared from frozen and stored material</th>
<th>Blanched before freezing</th>
<th>Cooked before freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>Isoleucine</td>
<td>129</td>
<td>122</td>
<td>136</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leucine</td>
<td>94</td>
<td>89</td>
<td>99</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lysine</td>
<td>107</td>
<td>103</td>
<td>112</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cysteine with methionine</td>
<td>84</td>
<td>72</td>
<td>72</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tyrosine with phenylalanine</td>
<td>139</td>
<td>104</td>
<td>104</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Threonine</td>
<td>108</td>
<td>100</td>
<td>111</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valine</td>
<td>146</td>
<td>133</td>
<td>145</td>
<td>134</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Histidine</td>
<td>147</td>
<td>139</td>
<td>153</td>
<td>137</td>
<td></td>
</tr>
<tr>
<td>EAA</td>
<td></td>
<td>117</td>
<td>106</td>
<td>114</td>
<td>106</td>
<td></td>
</tr>
</tbody>
</table>

CS – Chemical Score index  
EAA – Essential Amino Acid index
remaining essential amino acids. The highest CS index was found for histidine (137–153) and valine (133–146). The highest EAA index characterizing protein quality was registered by raw cauliflower (117), followed by the product from traditionally frozen cauliflower (114), with the lowest found in the remaining samples (106). The limiting amino acid in the protein of various vegetable species is usually methionine with cystine (Choi and Lee 1999, Diasolua-Ngudi et al. 2003, Korus et al. 2003, Kmiecik et al. 2008b), though it may also be lysine (Ishida et al. 2000, Lisiewska et al. 2004, Ayaz et al. 2006, Lisiewska et al. 2008a), histidine (Lopez et al. 1996) or tyrosine with phenylalanine (Kmiecik et al. 2009).

Conclusions

Cauliflower with green inflorescences is a good source of protein. Culinary processing and the freezing process did not result in a drastic decrease in amino acid content apart from tyrosine. The limiting amino acids of the first order for protein in both the raw material and products as eaten were methionine with cystine (Choi and Lee 1999, Diasolua-Ngudi et al. 2003, Korus et al. 2003, Kmiecik et al. 2008b), though it may also be lysine (Ishida et al. 2000, Lisiewska et al. 2004, Ayaz et al. 2006, Lisiewska et al. 2008a), histidine (Lopez et al. 1996) or tyrosine with phenylalanine (Kmiecik et al. 2009).

References


Kmiecik, W., Lisiewska, Z. & Korus, A. 2007. Retention of selected antioxidative compounds in raw brassicas depending on the method of preliminary processing of the raw mate-


Climatic potential and risks for apple growing by 2040

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The impact of climatic change in 1971–2040 on the potential production areas and risks to nine apple cultivars (*Malus domestica* Borkh.) was studied over continental Finland using agro-climatic indices and gridded daily mean (Tm) and minimum temperatures from the Rossby Centre regional atmospheric climate model (RCA3) with SRES A2. Point data on daily minimum temperatures from 14 weather stations and low and high warming scenarios were also used. From the 1970’s to the present day, the areas of successful maturing of fruits have strongly expanded northwards. It is predicted that in 2011–2040, the warming of climate will allow expansion of commercial production in the south-eastern lake area, and a wider selection of cultivars for home gardens up to latitudes 65–66°N. Risk of extremely low temperatures (Tm<−26 °C) has reduced from 1980’s to the present but may not reduce much more in 2011–2040. Risk to shoots from fluctuating temperatures in winter and spring is likely to increase under the high warming scenario, more in the south-west than in the south-east. Risk to trees from cold days (Tm<−15 °C) with a concurrent thin snow cover is not predicted to increase. In the western inland of the country, below latitude 63°N, and in the south-western coast areas the frost risk during flowering may increase, especially in the early flowering cultivars. In order to adapt to and gain from the climatic change, breeding and testing targets should be modified within five years and they should include reduced sensitivity to temperature fluctuation in winter, late flowering, and frost tolerance of flowers.

*Key-words:* Climate change, regional climate model, climatic index, winter injury, adaptation, acclimation
Introduction

In Finland, global climate change is expected to cause rise of seasonal mean temperatures in 2010–2039, relative to the mean values in 1961–1990, in winter by 1.2–5 °C, in spring by 1.1–4.2 °C, in summer (June-August) by 0.6–1.6 °C, and in fall (September–November) by 0.9–2.3 °C (Jylhä et al. 2004). The temperature change falls slightly outside the 95% interval of natural variation for all seasons. Changes in precipitation are in general positive, but mostly within the 95% interval of natural variation. In the past since 1960, mean daily temperatures in both spring (March-May) and winter (December-February) have risen by about 1 °C; winter temperatures have risen to even a slightly higher extent, but their inter-annual variation has been much wider than that for spring temperatures (Tuomenvirta 2004). The climatic warming before the mid-century seems is so strong that it is meaningful to study its consequences on apple growing in Finland, despite that inherent climatic variability and model uncertainties are very large compared to the magnitude of warming.

In relation to the observed warming of the seasons in Europe and North America, phenological time series show advancement in the all-leafing, flowering and fruiting of cultivated and natural species, including apple (Malus domestica Borkh) (Wolfe et al. 2005, Menzel et al. 2006, Eccel et al. 2009).

Austin and Hall (2001) assessed the impact of climatic warming on future apple production in the mild maritime climate of New Zealand. They concluded that the warming will have no discernible effect on growth and development during the next 25 years and only very limited effects before 2050. Eccel et al. (2009) studied risk of frost during flowering over the next 50 years by using statistically downscaled climate data and a thermal model calibrated to two sites at the alpine region of Tren-tino in Italy. They concluded that the risk of frost is more likely to reduce than increase.

As regards the cool climate in eastern Canada, the impact on apple production has been found more significant. Rochette et al. (2004) assessed the risks for apple production during fall, winter and spring by computing semi-empirical agro-climatic indices, using climatic data from a General Circulation Model with a spatial resolution of 3.75° × 3.75°. The date of the first fall frost, averaged across eastern Canada, is expected to be delayed by 10 days in 2010–2039 and by 16 days in 2040–2069, in comparison to 1961–1990, and correspondingly, the last spring frost (<–2 °C) would be advanced by 6 days in 2010–2039 and by 15 days in 2040–2069. The delay of the first fall frost was considered to enhance hardening in fall due to the prolongation of the period from the time point of induction of hardening by short daylength until the time of the frost. This conclusion, however, needs to be reconsidered after the finding by Heide and Prestrud (2005) that growth cessation and dormancy induction in apple are not influenced by photoperiod, but they are induced and controlled by low temperatures alone, which is contrary to the results by Howell and Weiser (1970a). The advance of the last spring frost, in connection with faster accumulation of growing degree days with the base temperature 5 °C (DD5), was predicted to reduce the frost risk to flower buds in the Continental North, to have no effect in the Maritimes and Ottawa Valley, and to increase the risk in the milder-climate southern Ontario.

An assessment by Winkler et al. (2002) in the Great Lakes region of the USA and Canada for 2025 to 2034 suggests that fruit-growing areas will experience a moderate prolongation of growing season, an increase in seasonal temperature accumulation, and a decrease in the frequency of freezing temperatures. They concluded that the risk of bud injury caused by fluctuating temperatures would increase in mild-climate southern Ontario, based on the accumulating temperature from the first frost in fall to the last frost in spring.

Our objective is to predict for Finland changes in suitability of apple cultivar types from the past decades to 2010–2040 and to assess what is needed to adapt to and possibly gain from the change. This study is limited to the first part of the 21st century because projecting the changes in the apple growing beyond the mid-century would not be very meaningful at this stage. Firstly, by the mid-cen-
tury, local fruit growing is likely to be affected at least as much by global economic and technological developments as by the climatic change. Secondly, the climate projections for Finland (Jylhä et al. 2004), based on the greenhouse gas emissions published in the Special Report on Emission Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al. 2000), do not differ greatly before the year 2050, but thereafter the different emission scenarios result in widely varying estimates of climatic warming, which reduces the practical value of the predictions concerning biological impacts. The CO₂ concentrations which are expected to be reached after 2050 (IPCC 2007) may also modify cold tolerance in winter and spring (Repo et al. 1996, Wayne et al. 1998) and the onset of hardening in fall (Taylor et al. 2008).

There are two parts in the estimation: potential and risks. The potential of an irrigated crop under cool climate is limited by warmness and length of growing seasons, described commonly by temperature accumulation over the season. The risks are caused by inadequate vegetative maturing due to cool summer (Tumanov et al. 1972, Lindén 2001), extreme coldness in winter (Quamme et al. 1976, Lindén et al. 1996, Caprio and Quamme 1999), fluctuating temperatures after dehardening late in winter and spring (Howell and Weiser 1970b, Ketchie and Beeman 1973, Coleman 1992, Caprio and Quamme 1999), and frost during flowering. The temporal patterns of weather leading to winter injury are rather well described in qualitative terms, but attempts to detect the causes by statistical analyses have been complicated by the fact that, in addition to large-scale climatic factors, the vulnerability of orchards to winter injuries is affected by the rootstock and cultivar resistance to cold, the age of trees, and the modification of local climate through the elevation and slope of the orchard, soil type, wind protection, and water bodies. This is well known in practice and established by surveys in Finland (Säkö and Pessala 1967) and in Quebec, Canada (Khanizadeh 2007).

Methods

Climate data and production of maps

Transient daily data on mean temperature ($T_m$), minimum temperature ($T_n$) and snow water equivalent in Finland during 1971–2040 were extracted from the European climate data for 1961–2100 with a spatial resolution of 0.44° on the rotated coordinate system simulated by the regional atmospheric climate model RCA3 at the Rossby Centre, Sweden (Kjellström et al. 2005). The data were based on SRES A2 (Nakicenovic et al. 2000) and a global climate model (GCM) simulation by ECHAM4/OPYC3 (Roeckner et al. 1999). It should be pointed out that also the past regional climate data were simulated, not measured. The climate data received from the Rossby Centre were processed with SAS software (SAS Institute Inc., Cary, NC, USA). The maps showing the gridded results under the geodesic coordinate system were drawn up by Mr. H. Ojanen using MapInfo software. The region of Åland Islands, west of south-western continental Finland, was not included in the data despite its being a locally important apple growing area, because the grid point of RCA3 covering the Åland Islands constitutes mainly of sea surface.

Point data on $T_m$ and $T_n$ in 1971–2000 from 14 weather stations operated by the Finnish Meteorological Institute (Table 1) were used for estimating the risk of fluctuating temperatures in winter and spring. The lowest and highest seasonal changes of mean temperature by 2010–2039 (SRES A2), given by Jylhä et al. (2004), were interpolated linearly with respect to day of year and year since 1961–1990 in order to obtain daily changes over the years 2011–2040. By adding the daily changes to the daily $T_m$ and $T_n$ values at the height of 2 m from the period 1971–2000 we obtained data sets for 2011–2040 with the same daily temperature range (DTR) as in 1971–2000, but with the mean and minimum values rising over the years.
The starting point for estimating the risk of frost during flowering is to predict the time of the flowering. In mild climates, the prediction is based on chilling temperatures in winter, which release the dormancy of buds, and on spring temperatures that drive the development of the buds (Richardson et al. 1974, Atkins and Morgan 1990, Legave et al. 2008). In climates with cold winters, the chilling requirement is met during winter under the present climatic conditions (Kronenberg 1979), and will easily be met in winter under the conditions expected by the mid-century in Finland (Jylhä et al. 2004). In the present climate, the timing of flowering in Quebec, Canada (Rochette et al. 2004) and in Finland (Ylämäki, unpublished) is predicted by a linear degree-day model without considering the chilling requirement.

The frost risk was first assessed using the point data in 1971–2000 and lowest and highest scenarios of temperature change given by Jylhä et al. (2004). For the point data, daily minimum temperature below –2 °C was set as the condition for frost during flowering. Under field conditions –2 °C at two metre height is generally a threshold for frost damage.

The flowering time was predicted by computing DD5 from the start of a year and using cultivar specific DD5 values for the start and end of flowering (Table 2), as observed at MTT Horticulture, Piikkiö (60°23′N, 22°33′E) (Ylämäki, unpublished). Under the semi-continental climate of Finland, the choice of base temperature above 0 °C affects very little the prediction as the temperatures rise quite rapidly in spring. The vulnerable period was set to start 20 DD5 before the start of flowering. Having

### Table 1. Weather stations for point data, location and altitude from sea level in metres. Mean annual number of frost days during flowering of cv. Samo during 1971–2000 and 2011–2040. Low and high scenario represent the lowest and highest seasonal temperature scenarios of temperature change given by Jylhä et al. (2004).

<table>
<thead>
<tr>
<th>LPNN</th>
<th>WMO</th>
<th>Station name</th>
<th>Location</th>
<th>Altitude</th>
<th>Frost days 1971–2000</th>
<th>Frost days 2011–40 Low scenario</th>
<th>Frost days 2011–40 High scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>0103</td>
<td>2828</td>
<td>Piikkiö</td>
<td>60°23′N 22°33′E</td>
<td>6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>1104</td>
<td>2762</td>
<td>Kokemäki</td>
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<td>Hyvinkää</td>
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<td>Lappeenranta</td>
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<td>3101</td>
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<td>Ylistaro</td>
<td>62°56′N 22°29′E</td>
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<td>3201</td>
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<td>Maaninka</td>
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<td>3801</td>
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<td>Oulu</td>
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<td>14</td>
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</tbody>
</table>

1LPNN National identification number  
2WMO World meteorological organisation identification code
estimated, from the point data, the number of frost days during flowering per decade, the \( T_n \) threshold for the RCA3 data was adjusted to give a roughly equal number of frost days as that found by means of the point data. Using RCA3 data annual numbers of frost days during flowering and from these means for periods 1981–2010 and 2011–2040 were computed.

**Harvesting of fruits.** The date of fruit maturing of the cultivars was computed from the RCA3 data based on DD5 accumulated from the start of the year. The number of years in a decade when fruits were predicted to mature successfully was computed to obtain the frequency of fruit maturing by decade. The frequency was scaled to the range from 0 to 1.

**Temperature accumulation requirements for vegetative maturity.** According to the experiments carried out at MTT Horticulture, Piikkiö, vegetative maturity of trees requires temperature accumulation that is approximately 100–150 DD5 higher than that needed by the harvesting of fruits (Tahvonen, unpublished). We used a rule that 100 DD5 on top of harvesting maturity, as given in Table 2, would provide vegetative maturity that will ensure stable yield year after year in the studied cultivars. The RCA3 data were used. The numbers of years in 1981–2010 and 2011–2040 when vegetative maturity of trees was predicted to be reached were computed to obtain the frequency of vegetative maturing in the respective periods. The frequency was scaled to the range from 0 to 1.

**Extreme cold and temperature fluctuation in winter.** Shoots of apple cultivars grown in cool climate areas can tolerate momentarily very low temperatures, down to –30 to –40 °C (Lindén et al. 1996, Quamme et al. 1976) when they are properly hardened. Yet, Caprio and Quamme (1999) concluded from a statistical analysis of apple production data in British Columbia, Canada, that low temperatures during November, December and February (–7 °C to –29 °C) were the main climatic factor limiting the apple production. Similarly, Lindén (2001) found that the variables indicating mid-winter severity, i.e., the monthly mean, minimum, and maximum temperatures from January to March, predicted well winter injuries in historical data in Finland. A precondition for the cold tolerance is that a growing season is warm enough for the termination of apical elongation and the subsequent hardening (Tumanov et al. 1972). There is evidence for Finland derived statistically by Lindén (2001) that low temperature accumulation during growing season has been associated with winter-kill years. In fall the hardening is initiated by low temperatures according to Heide and Prestrud (2005) but a rapid and permanent drop of temperatures from above the hardening level to a winter level will leave apple trees vulnerable to winter injury.

Fluctuating temperatures in winter cause bud and shoot damage in dehardened trees (Howell and Weiser 1970b, Ketchie and Beeman 1973).

### Table 2. Degree-day (base temperature 5 °C) requirements for flowering (flowers open) and harvest maturity of apple cultivars.

<table>
<thead>
<tr>
<th>Group</th>
<th>Cultivar</th>
<th>Flowering start</th>
<th>Flowering end</th>
<th>Fruit maturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>Pirja</td>
<td>170</td>
<td>210</td>
<td>970</td>
</tr>
<tr>
<td>Summer</td>
<td>Petteri</td>
<td>180</td>
<td>220</td>
<td>1120</td>
</tr>
<tr>
<td>Early fall</td>
<td>Samo</td>
<td>165</td>
<td>205</td>
<td>1160</td>
</tr>
<tr>
<td>Late fall</td>
<td>Melba</td>
<td>178</td>
<td>218</td>
<td>1190</td>
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<tr>
<td>Late fall</td>
<td>Sandra</td>
<td>190</td>
<td>230</td>
<td>1195</td>
</tr>
<tr>
<td>Late fall</td>
<td>Pekka</td>
<td>190</td>
<td>230</td>
<td>1230</td>
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<tr>
<td>Winter</td>
<td>Tobias</td>
<td>195</td>
<td>235</td>
<td>1240</td>
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<tr>
<td>Winter</td>
<td>Lobo</td>
<td>200</td>
<td>240</td>
<td>1300</td>
</tr>
<tr>
<td>Winter</td>
<td>Aroma</td>
<td>200</td>
<td>240</td>
<td>1340</td>
</tr>
</tbody>
</table>

**Requirement of temperature accumulation for vegetative maturity.**
The phenomenon emerged also in the surveys by Caprio and Quamme (1999) in British Columbia, Canada, and by Coleman (1992) in New Brunswick, Canada. Ketchie and Beeman (1973) showed that the temporal pattern of cold resistance is different from year to year making it difficult to find a single quantitative measure from experimental or survey data to predict the cold injury under variable climate.

(1) Days with $T_m$ below $-27^\circ C$ were considered to be extremely cold and potentially damaging to shoots or entire trees. The annual number of days with $T_m$ below this threshold in winter was computed from the RCA3 data. When $T_m$ is $-27^\circ C$, $T_n$ is below $-30^\circ C$ which is near the lowest temperatures momentarily tolerated by shoots, $-30$ to $-40^\circ C$ (Lindén et al. 1996, Quamme et al. 1976). Temperature fluctuation in winter was studied with point data using the lowest and highest warming scenario (Jylhä et al. 2004) and RCA3 data. The fluctuation was expressed as temperature accumulation in DD5 units from the start of year until the occurrence of the last daily minimum temperature ($T_n$) below the set threshold.

(2) For the point data, the $T_n$ threshold was $-15^\circ C$. Only $T_n$ below this threshold were considered damaging to shoots during the periods when $T_m$ exceeds $5^\circ C$. The threshold represents local practical opinion and is in the range found by Ketchie and Beeman (1973). In their experiment bark from young trees showed increased electrolyte conductance at $-10$ to $-25^\circ C$ when $T_x$ was above $5^\circ C$ in February in Washington, USA.

(3) Using the RCA3 data, 18 different $T_n$ threshold values were tried by stepping the $T_n$ threshold from $-15^\circ C$ to $2^\circ C$ by $1^\circ C$ increments.

Low temperatures with a concurrent thin snow cover. To establish the frequency of conditions injuring roots and rootstock, the number of days in winter with $T_n$ below $-15^\circ C$ and snow water equivalent below $15$ mm were computed from the RCA3 data. Water equivalent above $15$ mm was considered to significantly slow down fall of temperature in soil. There is no published data on the exact tolerance of apple roots and rootstock to cumulative cold. Yet, periods with $T_m$ under $-15^\circ C$ for several days are not common below the latitude $65^\circ N$ in Finland under the current climate but when such cold spells have occurred, dying of entire trees has been observed (Tahvonen, unpublished). Differences in cold tolerance between the cultivars were not taken into account.

Results

Due to lack of space graphs and tables for all cultivar and index combinations are not presented. For combinations not shown in graphs the results are described in the text.

Frost injury during flowering

Result for early fall type cv. Samo (Table 1) shows the trends found for all cultivars using the point data. Generally the risk is expected to stay at current level or decrease. The risk is high under present climatic conditions inland in western Finland (locations Ylistaro, Ähtäri) and in the north-west (Kajaani), but reduces both under the lowest and highest seasonal temperature scenarios. The risk will remain lowest at lake areas (Lappeenranta, Mikkeli in the south-east, Päijänne in the south), by the sea in the north (Oulu) and in the west (Kokemäki). Note that all cultivars do not mature at all sites (see results in chapter 2 below).

Based on RCA3 data, the start of flowering will advance from 1971–2000 to 2011–2040 by 6 to 10 days in the south-west, and 5 to 7 days in other areas. Using RCA3 data, the threshold values $4^\circ C$ and $5^\circ C$ yielded frost risk of the same magnitude as the $-2^\circ C$ threshold for the point data in central and western Finland. Using the threshold of $5^\circ C$ with the RCA3 data, the risk increased in 2011–2040 in the southern inland part of the country for all cultivars, but especially for the early flowering cultivars Pirja, Samo, Petteri, and Melba, while it decreased in the west and remained low in the east. Result for cv. Pirja is shown in Figure 1.
Maturing of fruits

From the 1970’s to the present day, the areas of successful maturing of fruits have strongly expanded northwards. An example of this is the potential maturing area of cv. Melba shown in Figures 2. During the following three decades, the maturing areas are predicted to continue expanding, though not as rapidly as in the past and mainly over central and western Finland where apple is grown only in home gardens. The very early maturing cultivars (cv. Pirja) are predicted to produce fully matured crops every year up to the latitudes 65 to 66°N in 2021–2040 (results not shown). Late maturing cvs Melba (Fig. 2), Sandra, Pekka and Tobias (results not shown) will mature every year up to the latitudes 61 to 62°N in the west and to the latitudes 62 to 63°N in the east, reflecting the effect of lake-richness in the east and hills in central and western Finland. Currently, the latest maturing, commercially grown cultivar on the continental Finland, Lobo, has produced mature fruits since 1991 only along the Baltic Sea in southern Finland and along the shores of large lakes in south-eastern Finland. In 2011–2040, Lobo is expected to mature in the whole southern part of the country up to the latitudes 61°N in the west and 62°N in the south-eastern lake area (results not shown). The cultivar Aroma, currently recommended only for the south-western archipelago, is expected to mature along the southern coast and with high probability also on the southern part of the eastern lake area (Fig. 3).

When studying the possible effect of hot days on fruit development by limiting the accumulation of temperature to 5 DD5 in a situation where the Tm exceeded 20 °C, it was found that the limitation did not have any significant effect on the spatial pattern of success of maturation for the majority of cultivars; only the maturing areas of the very late maturing cultivars Lobo and Aroma were locally reduced in southern inland Finland (results not shown).
Fig. 2. Change of spatial distribution of frequency of successful fruit maturing for cv. Melba by decade on scale 0–1. Legend frequency.

Fig. 3. Change of spatial distribution of frequency of successful fruit maturing for cv. Aroma by decade on scale 0–1. Legend frequency.
The areas where temperature accumulation during growing season is sufficient for successful vegetative maturity are expected to extend 200 to 300 km northwards during the period 2011–2040 in comparison to the period 1981–2010. The very early maturing cultivars (cv. Pirja) are expected to get well ready for winter every year in 2011–2040 up to the latitudes 64 to 65°N and in eight years out of ten up to the latitudes 65 to 66°N (Fig. 4). The slightly later summer cultivars (cv. Petteri, results not shown) and the fall cultivars Samo (Fig. 5), Melba and Sandra (results not shown), will get ready for the winter every year in the whole southern and central Finland. The late fall cv. Pekka (Fig. 6) and early winter cv. Tobias (results not shown) will terminate successfully their development in the

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**Fig. 4.** Change of spatial distribution of frequency of reaching vegetative maturity for cv. Pirja in 1981–2010 and 2011–2040 on scale 0–1. Legend frequency.

**Fig. 5.** Change of spatial distribution of frequency of reaching vegetative maturity for cv. Samo in 1981–2010 and 2011–2040 on scale 0–1. Legend frequency.
southern part of the country and in the south-eastern lake area. The latest maturing cultivars Lobo (Fig. 7) and Aroma (results not shown) were not able to prepare themselves for winter in most years in the continental Finland during the period 1981-2010.

During the next 30-year period they would be safe choices for orchards and home gardens only in the south-western coastal area and along lake shores in the south-east.

Fig. 6. Change of spatial distribution of frequency of reaching vegetative maturity for cv. Pekka in 1981–2010 and 2011–2040 on scale 0–1. Legend frequency.

Fig. 7. Change of spatial distribution of frequency of reaching vegetative maturity for cv. Lobo in 1981–2010 and 2011–2040 on scale 0–1. Legend frequency.
Extreme cold and temperature fluctuation in winter

(1) The frequency of very cold days ($T_m$ below $-27 \, ^\circ\text{C}$) has diminished from the 1970s to the 1990s and into the present decade. RCA3 does not predict further reduction of very cold days over the next three decades south of latitudes 65 to 66\(^\circ\)N where the coldness is an issue for apple growing in home gardens (results not shown). Above these latitudes the cultivars included in the study cannot be grown.

(2) Using the point data, it was found that with the lowest warming scenario, from the start of the year to the last day when $T_n$ was below $-15 \, ^\circ\text{C}$, temperature accumulation did not change appreciably at any station point (Table 3). With the highest scenario, the accumulation increased at all stations, most in the south-west (Piikkiö, Jokioinen, Kokemäki, Hyvinkää) being 14–17 DD5 and least in the east (Joensuu) and south-east (Lappeenranta, Mikkeli) in 2011–2040. In terms of days with $T_m$ above 5 \(^\circ\text{C}\) before the last $T_n$ was $-15 \, ^\circ\text{C}$, the change under the highest scenario was from near zero in 1971-2000 to 5–9 days in 2011–2040.

(3) With the RCA3 data, the $T_n$ threshold had to be raised to 2 \(^\circ\text{C}\) before 10–20 DD5 was accumulated in any part of country (results not shown), which means that RCA3 data cannot be used for assessing fluctuation late in winter and spring.

Low temperatures with a concurrent thin snow cover

According to the RCA3 data, the risk conditions with combined low temperature ($T_m$ below $-15 \, ^\circ\text{C}$) and thin snow cover (snow water equivalent less than 15 mm) would be infrequent during 2011–2040 within the entire area where apple can be grown commercially and in home gardens. The risk varies from decade to decade without any apparent trend (results not shown).

Discussion

The transient grided data of RCA3 facilitate the study of the impact of daily and annual variation on the spatial and temporal changes in the adaptation of apple cultivars. Kjellström et al. (2005) reported that, in northern Europe, the inter-annual variation simulated by RCA3 is close to the variation found in the ERA40 reanalysis data (Uppala et al. 2005). RCA3 simulates $T_m$ within $\pm 1 \, ^\circ\text{C}$ of ERA40 values, except in fall and winter in the north-eastern part of their model domain over Russia. Thus, if the performance of RCA3 for the past climate in northern Europe is considered to be a sufficient proof for its performance for the next three decades, $T_m$ values from RCA3 SRES A2 are satisfactorily reliable for our study.
However, there are some limitations in the data which are shared by other regional climate models (RCM). According to Kjellström et al. (2005), in the areas covering the central and southern parts of Finland, DTR of RCA3 was in spring and summer about 2 °C smaller than in the ERA40 data (Uppala et al. 2005). RCA3 overestimated T_n throughout a year in the area covering Finland: in southern Finland by 1 to 2 °C, and in northern Finland even more in winter and spring. Switching to another RCM or using averaged data from several RCMs would not offer a much better starting point. According to Kjellström et al. (2007) the ten RCMs they investigated, underestimated cold extremes in winter and warm extremes in summer by several degrees Celsius in northern Europe, including Finland. They assume that some fraction of the warm bias may be due to an effect of the boundary conditions originating from driving GCMs and not due to the RCMs.

Examination of the RCA3 data shows that it reflects the effects of the Baltic Sea coasts, large inland water bodies, such as the lake area in southeastern Finland, and large area altitude differences. Yet, because of the grid cell size it cannot detect the effects of smaller lakes and hill chains which are known to modify significantly local climate, affecting the suitability of any site for perennial crops. Furthermore, orchards are generally established in sites which are less prone to low night and winter temperatures than the entire RCA3 grid cell which contains the orchard sites. The limited spatial resolution of RCA3 and the bias in T_n mean that the potentials and risks mapped in this study need to be seen only as broadly describing the spatial and temporal trends and not as accurate predictions for any individual site in the mapping area. The data from RCA3 are best suitable for predicting the development of apple in summer and the risk of cold injuries caused by long lasting cold spells in winter. Short cold spikes in winter and during flowering are not well detected.

The frost risk during flowering in 2011–2040 in comparison to 1981–2010, based on RCA3 data, is expected remain at current level in most of the country, reduce in the west, but increase for all cultivars in the southern part of the country. The early flowering cultivars will be particularly vulnerable. The geographic differences arise naturally from the gradient of continentality of climate which increases from the south-west to the north-east of the Finland, and from the effect of lakes in the southeast. A point to mention for comparison in pest and yield potential studies is that the flowering is predicted to advance 5 to 10 days from 1971–2000 to 2011–2040.

The potential growing area where the temperature accumulation during growing season is sufficient for successful vegetative maturity and, consequently, for successful hardening, is expected to extend 200 to 300 km northwards during the period 2011–2040 in comparison to 1981–2010. Much of the expansion of the potential has already taken place since the 1970’s, which can be partially a result of temporary climatic variation or a result of the global warming trend. If the coming years show that the warming experienced this far is permanent, the expansion of the potential growing area of the cultivars may no longer proceed as rapidly. Rather, the effect of the climatic warming trend would be the stabilization of the expansion experienced since the 1990’s without any occasional retreat southwards, even despite of climatic variation in the coming decades.

The very early cultivars, for example, cv. Pirja, are expected to be able to terminate their vegetative development every year in 2011–2040 up to the latitudes 64 to 65°N and in eight years out of ten up to the latitudes 65 to 66°N. The slightly later summer cultivars, cv. Petteri, and the fall types, cvs Samo, Melba and Sandra, will get ready for the winter every year in the whole southern and central Finland. The late fall cultivars, cv. Pekka, and the early winter types, cv. Tobias, will reach vegetative maturity in the southern part of the country and in the south-eastern lake area. In 1981–2010, the latest maturing cultivars Lobo and Aroma could not fully prepare themselves for winter in most years in the continental Finland. During the next 30-year period they are expected to terminate successfully their development along the south-western Baltic Sea coast and along lake shores in the south-east Finland.
The very early maturing cultivars are predicted to produce mature fruits up to the latitudes 65 to 66°N in 2011–2040. Correspondingly, the late maturing cultivars, Melba, Sandra, Pekka, and Tobias, will mature up to the latitudes 62 to 64°N. In the decade 2031–2040, which in the simulations is assumed to be slightly cooler than the preceding decade 2021–2030, the maturing area extends further north in eastern Finland than in western parts of the country, reflecting the warming effect of large lakes in the east and the cooling effect of the hills in central and western inland Finland. Lobo, the latest maturing, commercially grown cultivar in the continental Finland, has since 1991 produced mature yield only on the Baltic Sea coast in south-western Finland and along the shores of the large lakes in south-eastern Finland. In 2011–2040, Lobo is expected to mature in the whole southern part of the country. The cultivar Aroma, currently recommended only for the south-western coast and the archipelago, is expected to mature in western continental Finland up to the latitude 61°N and in the south-eastern lake area up to the latitude 62°N. Even cultivars which require 1400 DD5 for fruit maturing may produce stable yield along the south-western coast and in the south-eastern lake area. With longer and warmer seasons, the prediction of fruit maturity of the currently latest maturing cultivars, Lobo and Aroma, would need to corrected for nonlinearity of the temperature response inland in southern Finland. The nonlinearity has been shown to be significant by Stanley et al. (2000), though in conditions with much longer growing seasons of New Zealand.

The frequency of extremely cold days has been observed to diminish from 1970s to the present (Tuomenvirta et al. 2000), which is caught by RCA3. According to RCA3 (Kjellström et al. 2005), the frequency is not expected to diminish further in the next three decades south of northern border of apple growing, latitudes 65 to 66°N. Yet, cold winter weather will not be uncommon in the eastern and northern part of the country. In the south-west and west, extreme coldness will be a lesser risk, but winter injuries may be caused by fluctuating temperatures after reduced dormancy late in winter and spring. Assuming similar distribution of temperatures in 2011–2040 as in 1971–2000 and the highest warming scenario (Jylhä et al. 2004), it is expected that apple trees will be in a clearly more vulnerable state in 2011–2040 when they meet the last very cold days (T<sub>n</sub><-15 °C). The change is larger in the west and south-west reflecting stronger expected warming of springs in the west (Jylhä et al. 2004). Under the lowest warming scenario, there would be no change in the risk of very cold days late in winter. It is also possible that the assumed variation of temperature in 2011–2040 is somewhat too large. In the last decades, DTR in winter and spring has reduced in Finland (Tuomenvirta et al. 2000) reflecting the global trend (Kaas and Frich 1995).

In the past, in winters when there has been little protective snow cover, low temperatures have been an occasional problem in central and western Finland. The RCA3 data suggest that the frequency of days with temperature below –15 °C when there is little protective snow cover should not increase. However, the reliability of this prediction may be low as the thickness of snow cover and its insulating value are rather hard to predict with a climate model.

High soil moisture and high temperatures in September as well as drought in August are known to interfere with the hardening of apple trees in the present climate (Lindén 2001). Yet, it is not clear whether it has been the soil moisture itself or the rather high temperatures at the time of drought that have affected trees in the past because it has been observed that high temperatures in July and August delay the development of irrigated trees and their fruits in Finland (Ylämäki, unpublished). RCA3 predicts only small changes in temperature and precipitation in October and November in Finland. Earlier, using data from several models, Jylhä et al. (2004) predicted a rise of 0.9 to 2.9 °C in fall temperatures during 2010–2039 from/in comparison to 1961–1990, and a slight increase of precipitation, 0 to 15%, over entire Finland. Change of average fall temperature is probably beneficial for the hardening of the late cultivars. A potential problem for the hardening lies in a possible sudden drop of temperature after a warm fall which will not disappear during 2010–2039 because the alternation of mar-
time western and continental north-eastern flows will stay. Perhaps, a more important change in fall is the rising importance of root and shoot canker caused by Phytophtora de Bary and Pythium Pringsheim species, and Nectria galligena Bres. which benefit from mild and wet conditions. There are already indications from the experimental orchard in Piikkiö that warm falls have aggravated injury from these pathogens.

In an ideal model, all the phases of development over a growing season and overwintering should condition the later phases, as they are qualitatively known to do (Howell and Weiser 1970b, Tumanov 1972, Ketchie and Beeman 1973, Coleman 1992, Caprio and Quamme 1999, Lindén 2001, Heide and Prestrud 2005, Khanizadeh 2007). This approach has long been pursued with forest trees but the models are still far from ready to predict the effect of climatic change (Hänninen 2006, Linkosalo et al. 2006, Hänninen and Kramer 2007). With fruit trees this approach would require more quantitative, cultivar specific information on response of trees to environment in winter, and a higher spatial resolution of projected climate data and better prediction ability of the daily and monthly ranges of temperature than provided by the current generation of RCMs.

In conclusion, the projected warming of climate is likely to be mostly beneficial to apple growing in Finland before the mid-century, as found in eastern Canada by Rochette et al. (2004) and for Great Lakes area in USA by Winkler et al. (2002), though exact comparisons between the studied regions cannot be made because the regional climates of the regions are different. The warming allows a wider selection of cultivars to home gardens, more productive cultivars in the south for commercial production and expansion of production in the south-eastern lake area. To introduce new cultivars and expand commercial production, winter hardiness and yield characteristics need to be tested at potential production sites. To increase the value of commercial production in the south, a programme for breeding and testing cultivars of late winter type should be initiated, with the aim of developing cultivars that produce fruits storable into spring, longer than any of the currently grown cultivars (Kinnanen et al. 2007). Adaption to climate change emphasizes existing general breeding targets which include low sensitivity to temperature fluctuation in winter, late flowering, frost tolerance of flowers, and better resistance to canker. The process from breeding to establishing actual orchards takes 15 to 20 years, and hence, breeding targets should be set within the next five years. Screening of the existing cultivars and rootstocks at sites where they have not been tested could start within 10 to 15 years, because the testing requires, at least, 5 to 10 years, or even more if no cold winters occur within that period.

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References


Compressive behaviour of the soil in buffer zones under different management practices in Finland

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Soil structure that favours infiltration is essential for successful functioning of vegetated buffer zones. We measured bulk density, air permeability and precompression stress in a clay soil (Vertic Cambisol) and a sandy loam (Haplic Regosol) in Finland, to identify management-related changes in the physical and mechanical properties in the surface soil of buffer zones. In addition, the impact of texture on these properties was studied at depths down to 180−200 cm. Soil cores (240 cm3) were sampled from a cultivated field, from buffer zones harvested by grazing (only in a clay soil) or by cutting and removing the vegetation, and from buffer zones covered with natural grass vegetation. The samples were equilibrated at a matric potential of –6 kPa and compressed at a normal stress range of 20−400 kPa (7 h), followed by stress removal (1 h). Generally, the clay soil was more compressible than the sandy loam. Due to trampling by cattle, the young grazed buffer zone (0−3 cm) had the largest bulk density and the smallest total porosity. For the grazed sites, reduced air permeability (2.7–5.1 × 10−5 m s−1) was found, compared with that of the buffer zone under natural vegetation (15–22 × 10−5 m s−1), indicating decreased pore continuity. Although the old grazed site was easily compressed, compared with the younger site, it showed a greater resilience capacity due to the protective cover of organic residues accumulated on the soil surface.

Key-words: buffer zone, air permeability, compressive behaviour, precompression stress, stress-displacement relationship, Vertic Cambisol, Haplic Regosol, Finland
Introduction

Vegetated buffer zones (BZs) have been successful in removing suspended solids and particle-bound nutrients from agricultural surface runoff in the Nordic climate (Syversen and Borch 2005, Uusi-Kämppä 2005). From a hydrological standpoint, the efficiency of the vegetated BZs is mainly based on the decrease in the amount and velocity of surface flow and the enhancement of infiltration (Dorioz et al. 2006), and hence proper soil structure is important for the successful functioning of BZs in terms of erosion and nutrient transportation by surface runoff water. Soil compression and shearing are widely recognized risks for structural deformation when heavy machinery is used in agriculture (e.g. Håkansson et al. 1988, Alakukku 1996a, 1996b, Peth et al. 2006) and in forestry (Horn et al. 2004). Similar problems were also attributed to trampling by wild ruminants in pasture-based forest ecosystems in Canada (Donkor et al. 2002), by cattle in intensive rotational grazing systems in the USA (Warren et al. 1986) or by cattle in pastures and vegetated BZs in Finland (Pietola et al. 2005, 2006). Owing to the reduction in volume of large pores and pore continuity, soil deformation reduces air permeability and hydraulic conductivity and therefore has an adverse impact on the functioning of pores for water and gas transport. It is not the textural pore space, i.e. matrix porosity, but the structural pore space that is susceptible to compaction (Richard et al. 2001). Mechanical disturbance of pore structure may accentuate soil erosion, leaching of nutrients by surface runoff, and organic matter loss, as well as restrict plant productivity (Horn et al. 1995). As a consequence, the critical function of BZs in minimizing nutrient inputs to surface water will diminish.

Soil deformation can be used as a collective term including compaction (air squeezed out of the soil), consolidation (water also squeezed out) and compression (combination of the former and soil movement, i.e. displacement) (Earl 1997). The corresponding effect can also be defined by the soil resilience, which is referred to as the soil’s capacity to recover its functional and structural integrity, and quantified as the rate or the extent of recovery after external stresses (Seybold et al. 1999). When soil is loaded, it is compressed, i.e. a decrease in total volume often occurs due to the movement of gas and water and the rearrangement of particles. This also implies a change in pore functioning. However, the extent of compression-induced soil structure deformation is dependent on both the internal (e.g. texture, structure, water content and interparticle bonds) and external properties such as the type of loading, loading time and frequency. Generally, fine-textured clay soils are more compressible than the coarser-textured silt soils under applied mechanical stress, and the soil strength increases with increasing degree of aggregation (Baumgartl and Horn 1991). The internal strength of soil, i.e. the resistance to external forces, can be quantified by the precompression stress. It is determined as the stress value that divides the compression curve into a portion of small, elastic and reversible soil deformation (the recompression line) and a portion of large, plastic and therefore irreversible deformation (the virgin compression line, VCL). Precompression stress is dependent on the maximum drying intensity and wetting and drying frequency, bulk density, clay content (i.e. soil texture) and time of loading (Lebert and Horn 1991, Alexandrou and Earl 1998, Keller et al. 2004, Peng et al. 2004, Fazekas and Horn 2005). However, Arvidsson and Keller (2004) provided evidence that precompression stress was not related to some of these properties.

The chemical properties of runoff water are traditionally used as the criteria for BZ effectiveness. Despite the fact that soil structure has an essential influence on the infiltration of water and solutes in BZs, the physical and mechanical properties of soil in the functioning of BZs have received substantially less attention. In the present study, the management-related differences in surface soil physical and mechanical properties in variously managed BZ areas were investigated to assess the impacts of BZ management practices on soil structure. The risk of surface soil deterioration resulting especially from grazing of clay soil was estimated, a practice that is allowed in BZ areas in Finland. Few mechanical measurements have been performed in Finnish agricultural soils (e.g. Pietola et al. 2005), and this is the first study in Finland in which compressive...
properties have been documented throughout the soil profiles, providing information on the depth-related properties of agricultural clay (Vertic Cambisol) and sandy loam (Haplic Regosol) soils.

**Material and methods**

**Experimental soils and soil sampling**

Soil samples were taken from Jokioinen in southwestern Finland (60°48’N, 23°28’E) and from Maaninka in central Finland (63°08’N, 27°19’E). The experimental soils were classified as a Vertic Cambisol at Jokioinen and as a Haplic Regosol at Maaninka, according to the World Reference Base for Soil Resources (WRB) system (Food and Agriculture Organization, FAO 2006). Based on the U.S. Department of Agriculture (USDA) texture classification system, the Jokioinen topsoil was silty clay and the subsoil was clay. At Maaninka the topsoil was loamy and the subsoil consisted of sandy loam. The long-term (1971–2000) mean annual temperature was 4.3 °C at Jokioinen and 2.8 °C at Maaninka, and the mean temperatures of the coldest (February) and warmest (July) months were −6.5 and 16.1 °C, and −9.6 and 16.5 °C, respectively. The mean annual precipitation was 607 mm at Jokioinen and 609 mm at Maaninka (Drebs et al. 2002). In winter 1998–1999, the average duration of the snow cover at Jokioinen was 148 d and at Kuopio Airport, close to Maaninka, 155 d (Finnish Meteorological Institute 2000). Evaporation makes up more than half of the precipitation in southern Finland and 30–40% in northern Finland.

For the Jokioinen clay soil and the Maaninka sandy loam soil, the experimental treatments of contiguous vegetated BZs (18 m × 10 m) with the cultivation techniques for arable soils adjacent to the BZs are given in Table 1. The BZs were established

<table>
<thead>
<tr>
<th>Site</th>
<th>Established before soil sampling, years</th>
<th>Vegetation</th>
<th>Harvesting</th>
<th>Grazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jokioinen, clay; Vertic Cambisol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old woody natural BZ</td>
<td>14</td>
<td>Natural; shrubs and trees&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Old natural BZ</td>
<td>14</td>
<td>Natural&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Old harvested BZ</td>
<td>14</td>
<td>Grass&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Annually</td>
<td>No</td>
</tr>
<tr>
<td>Young harvested BZ</td>
<td>3</td>
<td>Grass&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Annually</td>
<td>No</td>
</tr>
<tr>
<td>Young grazed BZ</td>
<td>3</td>
<td>Grass&lt;sup&gt;c&lt;/sup&gt;</td>
<td>No</td>
<td>Yes&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Old grazed BZ</td>
<td>14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Grass&lt;sup&gt;c&lt;/sup&gt;</td>
<td>No</td>
<td>Yes&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cultivated field</td>
<td>Ploughing to about 25-cm depth in autumn 2004 and preparation of the seedbed by harrowing just previous to sampling in spring 2005 before sowing with barley.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maaninka, sandy loam; Haplic Regosol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old natural BZ</td>
<td>10</td>
<td>Natural&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Young harvested BZ</td>
<td>3</td>
<td>Grass&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Annually</td>
<td>No</td>
</tr>
<tr>
<td>Cultivated field</td>
<td>Ploughing to about 20-cm depth in autumn 2004 and sowing with seed mixture of timothy and meadow fescue and a companion crop of barley in spring 2005. In previous years, the autumn-ploughed field was sowed with barley.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> BZ established in 1991 with grass species that were mostly cut but not always removed until grazed by cattle since 2001.

<sup>b</sup> Multispecies communities of wild hays and flowers (e.g. common bent *Agrostis capillaries* L., meadow vetchling *Lathyrus pratensis* L., dandelion *Taraxacum officinale* F.H. Wigg.), and also a thin stand of shrubs and hardwood trees (e.g. mountain currant *Ribes alpinum* L., guelder-rose *Viburnum opulus* L., small rowans *Sorbus aucuparia* L. and birches *Betula* L.) in the old woody BZ.

<sup>c</sup> Mainly timothy (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis* Huds.).

<sup>d</sup> 72, 234 and 128 cow grazing days ha<sup>−1</sup> yr<sup>−1</sup> in 2003, 2004 and 2005, respectively.

<sup>e</sup> An accurate stocking rate is unknown, but is probably comparable with the young grazed BZ.
in 2002 or 1991 (i.e. 3 or 14 years before soil sampling) between cultivated fields and main ditches receiving agricultural surface runoff and have been harvested by (i) grazing, (ii) cutting the grass and subsequently removing the residue or (iii) by not removing the vegetation. In general, all the BZ sites in question were utilized as cultivated fields for several years/decades prior to their establishment as BZs, with applications of nitrogen-phosphorus-potassium (NPK) compound fertilization, ploughing to a depth of about 20 cm in autumn and sowing with cereals (mainly barley *Hordium vulgare* L. and oat *Avena sativa* L.) in spring. Cultivation of soil was extended until the BZs were established, after which the sites were neither cultivated nor fertilized.

For determination of the air permeability and compression behaviour, undisturbed soil samples were taken from the surface layers of BZs and cultivated fields at depths of 0–3 cm, using a steel cylinder (240 cm³, height 30 mm, diameter 100 mm). The sampling line was set 2 m from the upper end of the sites subdivided into regular segments. In the Jokioinen clay soil, six replicate cores were taken on May 2, 2005, before vegetative growth and sowing. At the surface soil layer (0–11 cm), the mean soil moisture content, measured with time-domain reflectometry (TDR), varied from 26% to 37% for the driest cultivated field and the wettest old woody natural BZ soil, respectively. In the Maaninka sandy loam soil with mean moisture content of 33%, measured with TDR, five replicate cores were taken after emergence of vegetation on June 13, 2005. For the analysis of general soil properties, three replicate bulk soil samples were also taken from the surfaces of experimental soils (0–2.5 cm) in the BZs and cultivated fields.

Close to the experimental area covered with natural grass vegetation, a 200-cm-deep soil pit was excavated at Jokioinen (May 2, 2005) and eight horizons were identified. At Maaninka (June 13, 2005), there were six horizons in a 180-cm-deep soil pit that was close to the experimental area and also under natural grass vegetation. After morphological description and classification, the undisturbed soil samples (240 cm³) were taken from the middle of each genetic horizon with four (sandy loam, Haplic Regosol) or five (clay, Vertic Cambisol) replicates, as well as disturbed soil samples. Selected properties of the pedons are presented in Table 2.

### Table 2. Selected chemical and physical properties of the studied soils.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>pH</th>
<th>Org. carbon (%)</th>
<th>CECb (cmol(+)/kg⁻¹)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>Particle density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jokioinen, clay; Vertic Cambisol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0–6</td>
<td>6.2</td>
<td>5.4</td>
<td>28.3</td>
<td>51</td>
<td>42</td>
<td>7</td>
<td>2.20</td>
</tr>
<tr>
<td>Ap2</td>
<td>6–16</td>
<td>6.0</td>
<td>2.1</td>
<td>24.4</td>
<td>56</td>
<td>37</td>
<td>7</td>
<td>2.47</td>
</tr>
<tr>
<td>AB</td>
<td>16–38</td>
<td>6.0</td>
<td>2.2</td>
<td>25.2</td>
<td>55</td>
<td>38</td>
<td>7</td>
<td>2.46</td>
</tr>
<tr>
<td>Bw</td>
<td>38–45</td>
<td>6.4</td>
<td>0.9</td>
<td>21.6</td>
<td>57</td>
<td>38</td>
<td>5</td>
<td>2.47</td>
</tr>
<tr>
<td>Bt</td>
<td>45–90</td>
<td>7.0</td>
<td>0.4</td>
<td>27.7</td>
<td>80</td>
<td>18</td>
<td>2</td>
<td>2.56</td>
</tr>
<tr>
<td>BCtg1</td>
<td>90–115</td>
<td>7.3</td>
<td>0.3</td>
<td>28.9</td>
<td>86</td>
<td>13</td>
<td>1</td>
<td>2.49</td>
</tr>
<tr>
<td>BCtg2</td>
<td>115–165</td>
<td>7.5</td>
<td>0.3</td>
<td>28.6</td>
<td>93</td>
<td>6</td>
<td>1</td>
<td>2.51</td>
</tr>
<tr>
<td>Cg</td>
<td>165–200</td>
<td>7.7</td>
<td>0.3</td>
<td>23.3</td>
<td>87</td>
<td>13</td>
<td>0</td>
<td>2.50</td>
</tr>
<tr>
<td><strong>Maaninka, sandy loam; Haplic Regosol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap</td>
<td>0–30</td>
<td>6.6</td>
<td>1.4</td>
<td>9.4</td>
<td>8</td>
<td>47</td>
<td>45</td>
<td>2.59</td>
</tr>
<tr>
<td>C1</td>
<td>30–48</td>
<td>6.6</td>
<td>0.3</td>
<td>6.3</td>
<td>3</td>
<td>47</td>
<td>50</td>
<td>2.76</td>
</tr>
<tr>
<td>C2</td>
<td>48–69</td>
<td>6.7</td>
<td>&lt;0.1</td>
<td>5.1</td>
<td>2</td>
<td>44</td>
<td>54</td>
<td>2.68</td>
</tr>
<tr>
<td>C3</td>
<td>69–99</td>
<td>6.7</td>
<td>&lt;0.1</td>
<td>5.0</td>
<td>2</td>
<td>33</td>
<td>65</td>
<td>2.71</td>
</tr>
<tr>
<td>C4</td>
<td>99–120</td>
<td>6.8</td>
<td>&lt;0.1</td>
<td>5.5</td>
<td>5</td>
<td>52</td>
<td>43</td>
<td>2.78</td>
</tr>
<tr>
<td>C5</td>
<td>120–180</td>
<td>6.8</td>
<td>&lt;0.1</td>
<td>4.8</td>
<td>2</td>
<td>37</td>
<td>61</td>
<td>2.76</td>
</tr>
</tbody>
</table>

a pH measured in H₂O suspension. b CEC: cation exchange capacity at pH 7.0.

*USDA texture system: clay < 0.002 mm; silt 0.002–0.05 mm; sand > 0.05 mm."
Laboratory measurements

The bulk soil samples were dried at 37 °C and passed through a 2-mm sieve. The particle-size distribution was determined with the pipette method (Elonen 1971), particle density with a stopped bottle pycnometer method, total organic carbon content with a Leco® CHN 900 induction furnace, and soil pH measured in a deionized water suspension (1:2.5 soil-to-solution ratio). For the determination of cation exchange capacity (CEC), the Ca²⁺, Mg²⁺, K⁺ and Na⁺ and H⁺+Al³⁺ were extracted with 1 M CH₃COONH₄ (pH 7) at a soil-to-solution ratio of 1:5.

The bottoms of the undisturbed soil cores were sealed with two filter papers one upon another (Schleicher & Schuell MicroScience 595). Thereafter, the cores were saturated from the bottom and equilibrated to a –6-kPa matric potential in sand boxes. Prior to the compression, the air permeability was determined by the apparatus illustrated in Horn et al. (2004). The air permeability \( k_l \) (m s⁻¹) was calculated by the equation

\[
k_l = \rho_l \times g \times \left[ \frac{(D V \times l)}{(D t \times D p \times A)} \right],
\]

where \( \rho_l \) is the air density (1.204 kg m⁻³ at 20 °C), \( g \) the gravitational acceleration (9.81 m s⁻²), \( D V/Dt \) the amount of air passed through the sample per time (m³ s⁻¹), \( l \) the height of the cylinder (m), \( Dp \) the applied air pressure (hPa) and \( A \) the surface area of the sample (m²).

The samples were stressed statically with 20, 40, 70, 100, 200 and 400 kPa for 7 hours, using the confined compression device. The compaction-dependent soil vertical displacements or settlement (displacement sensor) and the changes in pore-water pressure (ceramic microtensiometer) were recorded automatically with a resolution of 0.001 mm and 0.001 hPa during loading (compression) and unloading (rebound or resilience) for 1 h. At each experimental site, four to six single data points from the confined compression test were linked with the compression curve, and a second-order polynomial curve was fitted to describe the relationship between the soil vertical displacement (mm) on the normal scale and the applied stress (kPa) on the logarithmic scale. The precompression stress was estimated, using a graphical procedure of Casagrande’s method (1936). Shortly, the stress-displacement curve was subdivided into the recompression curve in the lower stress range of the upper portion of the curve and the VCL at the higher stress level, after which the precompression value was derived from the curve. The initial dry bulk density as well as the volumetric water content was calculated after drying at 105 °C for 48 h. The total porosity was estimated from the dry bulk density and the particle density.

The means and the standard deviations (± SD) were calculated from the replicates taken within the nonreplicated treatments or nonreplicated horizons. Statistically significant differences between the treatments or horizons were tested with analysis of variance using the SAS 9.1 program. The standard error of the mean (SE), the standard error of the difference (SED) and the Student’s T-test least significant difference (LSD) at the \( p < 0.05 \) level of significance were calculated separately over the treatments or horizons according to each soil type, enabling the reader to estimate the statistically significant differences.

Results

The pedons

The bulk densities were substantially greater in the horizons of the Maaninka sandy loam soil (Haplic Regosol) than those of the Jokioinen clay soil (Vertic Cambisol) (Table 3). In the clay soil, the bulk density gradually increased with depth down to the Bt horizon (45–90 cm) and then decreased again. For the sandy loam, the bulk density was greatest in the two uppermost horizons, attaining maximal levels at depths of 30–48 cm in the C1 horizon. The total porosity was determined from the bulk density and thus the coarser-textured sandy loam horizons tended to be less porous than the finer-textured clay horizons. In the horizons closer to the surface, the air permeability values were substantially greater in
the clay soil than in the sandy loam soil. In the clay soil, there was a sharp decline in air permeability at depths of 38–45 cm in the Bw horizon and another decline to as low as 0.3 × 10^{-5} m s^{-1} at 90–115 cm (the BCtg1 horizon), whereas there was a relatively smaller drop to 0.2 × 10^{-5} m s^{-1} at 48–69-cm depths (the C2 horizon) in the sandy loam soil.

Figure 1 shows the response of the soils to the applied stresses expressed as (semi)log stress-displacement curves for the horizons of the Jokioinen clay soil and the Maaninka sandy loam at a matric potential of –6 kPa. Even though the average vertical displacement over the applied stresses generally decreased from top to bottom throughout the soil profiles, the clay soil and the sandy loam exhibited very different compression behaviours. The amount of vertical displacement and rebound, measured at the end of the loading and unloading step, were more pronounced for the horizons of the clay soil than for those of the sandy loam. The relationship of the rebound to the original displacement, however, was very similar, being 11–41% for the clay soil and 18–44% for the sandy loam over the applied stresses. For the soil horizons, the estimates of the precompression stresses on the basis of Casagrande’s method were generally lower for the clay soil (< 60 kPa) than for the sandy loam (< 110 kPa) (data not shown).

Table 3. Initial bulk density, volumetric water content, total porosity and air permeability (mean ± SD) for the genetic soil horizons at a matric potential of –6 kPa. The SE, SED and LSD are presented separately over the horizons, according to the soil type (n = 5 for clay and n = 4 for sandy loam).

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Bulk density (g cm^{-3})</th>
<th>Water content (cm^{3} cm^{-3})</th>
<th>Total porosity (cm^{3} cm^{-3})</th>
<th>Air permeability (10^{-5} m s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jokioinen, clay; Vertic Cambisol (n = 5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0–6</td>
<td>0.98 ± 0.16</td>
<td>0.41 ± 0.03</td>
<td>0.55 ± 0.07</td>
<td>35.0 ± 12.6</td>
</tr>
<tr>
<td>Ap2</td>
<td>6–16</td>
<td>1.14 ± 0.06</td>
<td>0.36 ± 0.02</td>
<td>0.54 ± 0.02</td>
<td>52.1 ± 14.0</td>
</tr>
<tr>
<td>AB</td>
<td>16–38</td>
<td>1.25 ± 0.07</td>
<td>0.38 ± 0.02</td>
<td>0.49 ± 0.03</td>
<td>28.4 ± 13.1</td>
</tr>
<tr>
<td>Bw</td>
<td>38–45</td>
<td>1.34 ± 0.08</td>
<td>0.39 ± 0.03</td>
<td>0.46 ± 0.03</td>
<td>9.7 ± 7.2</td>
</tr>
<tr>
<td>Bt</td>
<td>45–90</td>
<td>1.38 ± 0.04</td>
<td>0.44 ± 0.01</td>
<td>0.46 ± 0.01</td>
<td>9.3 ± 17.1</td>
</tr>
<tr>
<td>BCtg1</td>
<td>90–115</td>
<td>1.19 ± 0.01</td>
<td>0.52 ± 0.02</td>
<td>0.54 ± 0.00</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>BCtg2</td>
<td>115–165</td>
<td>0.98 ± 0.04</td>
<td>0.57 ± 0.03</td>
<td>0.61 ± 0.01</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Cg</td>
<td>165–200</td>
<td>1.06 ± 0.10</td>
<td>0.55 ± 0.02</td>
<td>0.58 ± 0.04</td>
<td>0.9 ± 1.4</td>
</tr>
<tr>
<td>Maaninka, sandy loam; Haplic Regosol (n = 4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap</td>
<td>0–30</td>
<td>1.56 ± 0.07</td>
<td>0.40 ± 0.02</td>
<td>0.42 ± 0.03</td>
<td>1.0 ± 1.3</td>
</tr>
<tr>
<td>C1</td>
<td>30–48</td>
<td>1.63 ± 0.09</td>
<td>0.39 ± 0.02</td>
<td>0.41 ± 0.03</td>
<td>1.7 ± 1.6</td>
</tr>
<tr>
<td>C2</td>
<td>48–69</td>
<td>1.32 ± 0.01</td>
<td>0.46 ± 0.03</td>
<td>0.51 ± 0.00</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>C3</td>
<td>69–99</td>
<td>1.48 ± 0.03</td>
<td>0.39 ± 0.03</td>
<td>0.46 ± 0.01</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>C4</td>
<td>99–120</td>
<td>1.45 ± 0.04</td>
<td>0.40 ± 0.02</td>
<td>0.48 ± 0.01</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>C5</td>
<td>120–180</td>
<td>1.39 ± 0.04</td>
<td>0.36 ± 0.03</td>
<td>0.50 ± 0.02</td>
<td>0.6 ± 0.2</td>
</tr>
</tbody>
</table>

SE = standard error of the mean, SED = standard error of the difference; LSD = Student’s T-test least significant difference (p < 0.05);
* The mean with different n is not included in the SE, SED or LSD.
The surface soil

In the surface layer (0–2.5 cm) of the clay soil, where multiple management practices were used in the BZs, the level of organic carbon ranged from 2.8% (± 0.1%, SD) to 7.0% (± 1.9%), increasing with the age of the grassy vegetation due to continued litter accumulation on the soil surface, and was markedly higher than in the cultivated field (1.8% ± 0.2%) (data not shown in detail). The particle density decreased from 2.47 (± 0.04) to 2.25 (± 0.08) g cm⁻³ with the increase in organic carbon. In the sandy loam soil with particle densities of 2.56 (± 0.04) – 2.64 (± 0.05) g cm⁻³, the organic carbon was higher in the soil under natural vegetation (5.5% ± 0.4%) than under young grass (2.1% ± 0.0%) or in the cultivated field (1.8% ± 0.0%).

In the clay soil at depths of 0–3 cm, the initial dry bulk density was significantly higher in the young grazed BZ than in the old grazed and old natural BZs, and in the mechanically loosened cultivated field (Table 4). In the sandy loam soil, the bulk density was greatest in the cultivated field. For both soils, the air permeability values varied by the same order of magnitude from a minimum of 2.2 × 10⁻⁵ m s⁻¹ in the cultivated sandy loam field to a maximum of 29 × 10⁻⁵ m s⁻¹ in the cultivated clay. In the clay soil, the grazed BZ sites showed considerably lower air permeability levels than the other sites.

At 0–3-cm depths, the compression curves of the variously managed surface soils were remarkably comparable for the Jokioinen clay soil and the Maaninka sandy loam, at a matric potential of –6 kPa (Fig. 2). In the stress-displacement curves, there were no clear transitions from the small and elastic (i.e. reversible) to the larger and plastic (i.e. irreversible) deformations. The values of the precompression stresses ranged from 40 to 60 kPa for both soils, regardless of the management practices (data not shown in detail). For example, at an applied stress of 200 kPa, the vertical displacement varied from a minimum of 6.3 mm with a 1.3-mm rebound for the young grazed BZ to a maximum of 9.6 mm with a 2.3-mm rebound for the old grazed BZ. Generally, the extent of the displacement and rebound was greater for the older BZ sites of lower bulk densities and higher organic carbon contents (Fig.
Table 4. Initial bulk density, volumetric water content, total porosity and air permeability (mean ± SD) for the surface soils (0–3 cm) of vegetated BZs and cultivated fields at a matric potential of –6 kPa. The SE, SED and LSD are presented separately over the treatments, according to the soil type (n = 6 for clay and n = 5 for sandy loam).

<table>
<thead>
<tr>
<th>Site</th>
<th>Bulk density (g cm⁻³)</th>
<th>Water content (cm³ cm⁻³)</th>
<th>Total porosity (cm³ cm⁻³)</th>
<th>Air permeability (10⁻⁵ m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jokioinen, clay; Vertic Cambisol (n = 6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old woody natural BZ</td>
<td>1.06 ± 0.14</td>
<td>0.42 ± 0.04</td>
<td>0.53 ± 0.06</td>
<td>22.1 ± 23.7 *</td>
</tr>
<tr>
<td>Old natural BZ</td>
<td>0.95 ± 0.07</td>
<td>0.45 ± 0.04</td>
<td>0.60 ± 0.03</td>
<td>15.0 ± 18.6 *</td>
</tr>
<tr>
<td>Old harvested BZ</td>
<td>1.04 ± 0.10</td>
<td>0.43 ± 0.04</td>
<td>0.56 ± 0.04</td>
<td>24.7 ± 11.4 *</td>
</tr>
<tr>
<td>Old grazed BZ</td>
<td>0.97 ± 0.09</td>
<td>0.44 ± 0.03</td>
<td>0.59 ± 0.04</td>
<td>5.1 ± 3.1</td>
</tr>
<tr>
<td>Young grazed BZ</td>
<td>1.17 ± 0.09</td>
<td>0.45 ± 0.03</td>
<td>0.51 ± 0.04</td>
<td>2.7 ± 2.4</td>
</tr>
<tr>
<td>Young harvested BZ</td>
<td>1.08 ± 0.06</td>
<td>0.40 ± 0.03</td>
<td>0.56 ± 0.02</td>
<td>24.1 ± 16.7</td>
</tr>
<tr>
<td>Cultivated field</td>
<td>0.94 ± 0.03 *</td>
<td>0.33 ± 0.01 *</td>
<td>0.61 ± 0.01 *</td>
<td>28.7 ± 13.6</td>
</tr>
<tr>
<td>SE</td>
<td>0.04</td>
<td>SE 0.01</td>
<td>SE 0.02</td>
<td>SE 4.5</td>
</tr>
<tr>
<td>SED</td>
<td>0.05</td>
<td>SED 0.02</td>
<td>SED 0.02</td>
<td>SED 6.3</td>
</tr>
<tr>
<td>LSD</td>
<td>0.11</td>
<td>LSD 0.04</td>
<td>LSD 0.05</td>
<td>LSD 13.2</td>
</tr>
<tr>
<td>Maaninka, sandy loam; Haplic Regosol (n = 5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old natural BZ</td>
<td>0.88 ± 0.12</td>
<td>0.41 ± 0.04</td>
<td>0.66 ± 0.05</td>
<td>25.0 ± 13.0</td>
</tr>
<tr>
<td>Young harvested BZ</td>
<td>1.11 ± 0.13</td>
<td>0.39 ± 0.04</td>
<td>0.58 ± 0.05</td>
<td>28.2 ± 21.7</td>
</tr>
<tr>
<td>Cultivated field</td>
<td>1.24 ± 0.08</td>
<td>0.35 ± 0.02</td>
<td>0.51 ± 0.03</td>
<td>2.2 ± 1.3</td>
</tr>
<tr>
<td>SE</td>
<td>0.05</td>
<td>SE 0.01</td>
<td>SE 0.02</td>
<td>SE 6.5</td>
</tr>
<tr>
<td>SED</td>
<td>0.07</td>
<td>SED 0.02</td>
<td>SED 0.03</td>
<td>SED 9.2</td>
</tr>
<tr>
<td>LSD</td>
<td>0.15</td>
<td>LSD 0.04</td>
<td>LSD 0.06</td>
<td>LSD 20.1</td>
</tr>
</tbody>
</table>

SE = standard error of the mean, SED = standard error of the difference; LSD = Student’s T-test least significant difference (p < 0.05).
* The mean with different n is not included in the SE, SED and LSD.

Fig. 2. Examples of vertical displacement (mm) as a function of the logarithm of the applied stress (kPa) for the differently managed surface soils (0–3 cm) of the Jokioinen clay and Maaninka sandy loam at a matric potential of –6 kPa. A second-order polynomial curve was fitted and the precompression stress was estimated, using Casagrande’s procedure.
3). The vertical displacement also resulted in a decrease in the sample volume or an increase in bulk density. An applied stress of 200 kPa caused decreases of 21–32% and 26–31% in the sample volume for the clay and sandy loam soils, respectively, whereas following the stress removal, the final changes were 16–26% and 23–26%, respectively. As a result of the elastic rebound, the surface soils of both textures recovered 0.01–0.16 g cm\(^{-3}\) from the build-up of the bulk density over the applied stresses and management practices; however, the final changes varied from 0.07 to 0.46 g cm\(^{-3}\). Generally, the susceptibility to compression at clay soil depths of 0–3 cm decreased with decreasing air-filled porosity in the following order: cultivated field > old grazed BZ > old natural BZ > old harvested BZ > young harvested BZ > old woody natural BZ > young grazed BZ. For the sandy loam soil, the susceptibility to compression was as follows: old natural BZ > young harvested BZ > cultivated field.

In the Jokioinen (Vertic Cambisol) and Maaninka (Haplic Regosol) pedons, the parent material consisted of fine-textured, postglacial sediments mainly deposited in brackish water during the Yoldia Sea stage (11,600–10,800 years B.P.). The fine clay fraction was mostly composed of illite, chlorite, vermiculite and amorphous material, whereas the contents of the feldspar and quartz increased with increasing particle size (Sippola 1974), predominantly in the sandy loam. Consistent with the concept of general compressive behaviour for different soil textures under applied mechanical stresses, the horizons of the fine-textured Jokioinen clay soil were more compressible than those of the coarser-textured Maaninka sandy loam soil, probably due to soil texture rather than to management practices. The topmost horizons were mechanically loosened to a normal ploughing depth of about 20 cm. The soil was strongest below the plough layer due to the presence of a denser plough pan that has persisted as long as 10 years in the originally ploughed Maaninka sandy loam. In

**Discussion**

**Depth-related characteristics**

![Fig. 3. Maximum and minimum rebound (mm) subsequent to the compression (mm) measured at the end of the loading (7 h) and unloading (1 h) step as a function of the logarithm of the applied stress (kPa) for the differently managed surface soils (0–3 cm) of the Jokioinen clay and Maaninka sandy loam at a matric potential of –6 kPa. Compression = thick line, filled symbol; Rebound = thin line, unfilled symbol.](image_url)
the Jokioinen clay soil, the plough pan was not as clearly distinguishable after 14 years. Our findings that the uppermost horizons with a looser structure were more compressible than the deeper horizons with a prismatic and blocky structure supported those of Baumgartl and Horn (1991).

Despite the increasing clay content, soil compressibility or resistance to volume decrease under an externally applied load substantially increased with depth, although without corresponding changes in the precompression stress values. This was inconsistent with the results summarized by Horn et al. (1995) that the C horizons of three soil types were weakest and may be partly attributable to prevention of further compression resulting from the decrease in pore volume and the retardation in drainage of excess water by inadequate hydraulic conductivity, pore continuity and hydraulic gradients (Baumgartl and Horn 1991). The high soil compressibility was also caused by the relatively high water contents at a matric potential of –6 kPa. In the deepest horizons, lower values of air permeability, especially in the clay soil, indicate the absence of macropores and lack of connectivity created by faunal and root activity. The low bulk density and high total porosity, despite the very low organic carbon content, showed that a massive and weakly aggregated card-house structure, inherited from the sediment parent material, still prevailed below 90 cm. Even if the clay mineralogy and high clay content of up to 93% potentially contributed to crack formation as a result of swelling and shrinking through the wetting and drying cycles, the deepest horizons below the depth of the subsurface drainage pipes (about 1 m) probably would remain wet throughout the year. Therefore, these horizons have weakly developed structures and the soil is still unripe.

### Management-related differences of buffer zones

The internal strength of soils and soil profiles can be quantified by precompression stress, which is determined by pedogenic processes, anthropogenic effects and hydraulic site-specific conditions (Horn et al. 2004). In Sweden, the precompression stress values for arable soils generally classified as Eutric Cambisols (6–86% clay) were 106 and 139 kPa in the topsoil (0–30 cm) and 129 and 179 kPa in the subsoil (30–60 cm) at matric potential values of –0.5 kPa and more intensively dried conditions of –60 kPa, respectively (Arvidsson and Keller 2004). These values are greater than those of the present study. Our sampling time reflects the conditions prevailing after winter when the surface soil structure is weakest, and hence the soil strength is very low as suggested by Rasa et al. (2009). However, the accuracy of the precompression stress values determined according to the Casagrande method is inadequate, due to the limitations in the designed experiment. In the grazed BZs, the internal soil strength was considerably lower than the external stress caused by single hoof pressure of about 500 kPa divided equally among hoofs (125 kPa), based on a body weight of 500 kg and hoof contact area of 100 cm². Consequently, trampling by cattle did not result in additional increases in soil strength, which is in accordance with Horn et al. (2004), who found no notable effects of trampling by horses (650 kg) on precompression stress in their forest-harvesting experiment. However, soil strength may increase due to compaction, or on the other hand, decrease due to destruction of the existing aggregation by shearing (Horn et al. 1995).

Stone and Larson (1980) measured a decrease of < 0.05 g cm⁻³ in the bulk density along with a release in mechanical stresses (0.1–1.0 MPa). Despite the relatively small differences in bulk density, Larson and Gupta (1980) hypothesized that remarkable changes in pore structure may occur due to distinctive changes in pore-water pressure. We found greater rebound of up to 0.16 g cm⁻³ (20–400 kPa), which indicates that these surface soils are extremely susceptible to structural deformation. Furthermore, the soils were not strong enough to withstand applied stresses, and thus we noted considerable plastic deformations, even under the lowest applied stress of 20 kPa. However, these findings can be partly explained by the early sampling times and equilibration of the samples at a matric potential of –6 kPa, similar to the field ca-
pacity. Wetter soils increasingly lower the stability, and subsequently the proportion of elastic to plastic deformation may be more pronounced.

The BZ sites under vegetation cover showed substantially higher resilience capacity than the cultivated fields. The old grazed BZ of relatively low resistance displayed a higher degree of elastic rebound than the young grazed BZ of high resistance. McBride and Watson (1990) also observed the largest degree of rebound (0.018–0.075 g cm⁻³) upon stress removal (1.0 MPa) for structured unsaturated soil of the highest measured organic matter content and the lowest dry bulk density. Kuan et al. (2007), on the other hand, noted that repacked soils in Scotland (0–31% clay) with the greatest organic carbon levels (1.7–30%) possessed poor resistance to but good recovery from compressive stress. This trend also occurred for the BZ surface soils in the present study. We observed here that a much larger amount of partially decomposed organic material accumulated on our old grazed BZ soil surface, resulting from the management practice of no vegetation removal and from cattle dung. The beneficial effect of organic matter was confirmed by Zhang et al. (2005), who found that the rebound increased with the addition of particulate peat (0–50 g kg⁻¹), stating that organic matter acted as a mechanical spring, and hence the decrease in soil resistance to stresses is compensated by the improvement in physical resilience after stress release. Therefore, organic residues of low density and high elasticity may protect the soil surface and improve its recovery potential. Consequently, BZs should not be grazed before the organic cover has developed on the soil surface. Due to the higher capacity of soil to recover from occasional compactive disturbances, as opposed to frequent disturbances such as livestock trampling (Seybold et al. 1999), regular grazing may pose a higher risk for the structural deterioration of soil. On the other hand, recovery of the soil structure subsequent to the period of no trampling may be promoted in clay soil of higher shrinking and swelling capacity by the wet-dry and freeze-thaw cycles compared with sandy loam soil.

Despite the differences in the initial bulk densities, the minimum values of air permeability were measured for both of the grazed BZs, probably resulting from soil deformation and disturbance of the pore system by shearing rather than vertical compaction. Air permeability is used as an indicator of pore continuity (Dexter 1997) and is considered very sensitive to soil structural changes resulting from management practices and biological activity (Blackwell et al. 1990). In addition, Iversen et al. (2001) pointed out the close relationship between air permeability and saturated hydraulic conductivity. Accordingly, the reduced air permeability measured for grazed sites indicates changes in the soil structure and lack of a continuous network of air-filled pores and is conducive to reduced hydraulic conductivity. For the same experimental clay soil sites, the preliminary results of Pietola et al. (2006) showed that trampling decreased the flow rate of water after a 15-min infiltration to 10–20 cm h⁻¹, compared with that of 40 cm h⁻¹ for the old woody natural BZ and 60 cm h⁻¹ for the old harvested BZ measured in situ in early May 2005 under unsaturated conditions. Furthermore, Pietola et al. (2005) showed that the steady-state infiltration rate decreased from 7.2 to 1.0 cm h⁻¹ with increasing trampling damage in heavy clay soil. If the infiltration capacity decreases, water accumulation on the soil surface may also expose the soil to further trampling damage.

**Conclusions**

The lowest values of air permeability for the grazed buffer zones (0–3 cm) indicated the reduction in connectivity of the pore network and thus also in the hydraulic conductivity. Data from the confined compression test showed that the precompression stress values were rather low throughout the soils, probably due to the sampling which was done after winter when the soil structure is weak. Trampling by cattle did not result in additional increases in the precompression stress values; however, the soil compressive behaviour differed substantially between the two grazed sites. The old grazed buffer zone that had the low initial bulk density tended to
be easily compressed compared with the younger ones. However, the old grazed buffer zone was able to recover more elastically subsequent to stress removal than the young grazed buffer zone of higher bulk density, due to the organic matter accumulated on the soil surface. Thus, we emphasize the importance of preserving surface soil and soil structure without disturbances under vegetation and recommend grazing only after the organic cover has developed on the soil surface of buffer zones. Under undisturbed conditions with no grazing, the surface soil of the buffers zones probably exhibited a better rearrangement of particles, pore sizes and systems, and consequently the management-related changes were not as clearly distinguishable.

This study was the first in Finland to document the mechanical properties of arable soils, which are necessary for determining stress limits and assess the susceptibility of different soil types to compaction and irreversible soil deformation. The trends found here need to be verified, using different soils with several replicates to result in more accurate recommendations for sustainable management strategies of buffer zones. Further studies will therefore need to focus on determination of the compression behaviour and precompaction stresses under dynamic, cyclic loading conditions, like those caused by animal trampling.

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Nitrogen fertilization and yield formation of potato during a short growing period

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The effects various rates of nitrogen application on accumulation of dry matter and nitrogen in potato (Solanum tuberosum L.) were studied during a short growing period of 140–180 days, at MTT Agrifood Research Finland in 2000–2001. The treatments were 0, 60 and 120 kg N ha\(^{-1}\) and the potato cultivars tested were Van Gogh and Nicola. Four successive harvests were made during the course of the experiment to monitor changes in the accumulation of dry matter and nitrogen over the season. Applications of nitrogen substantially increased haulm dry matter accumulation and to an even greater extent their nitrogen contents. The highest dry matter values were generally registered at 120 kg N ha\(^{-1}\). Dry matter and nitrogen content of haulms started to decline during the later part of season and most nitrogen was relocated to tubers. The results suggest that an application of only 60 kg N ha\(^{-1}\) was sufficient to promote rapid canopy development and there were only small reductions in dry matter and nitrogen accumulation until late in the season when the canopy started to senesce as nitrogen supply diminished. Tuber yield, plant dry matter and nitrogen accumulation at maturity were related to crop nitrogen supply. Although application of the high rate, 120 N kg ha\(^{-1}\), resulted in a significant increase in dry matter accumulation, this was not reflected in the profit because the higher nitrogen application reduced dry matter content of tubers by 2.6% in 2000 and by 1.1% in 2001 relative to the use of 60 kg N ha\(^{-1}\). Apparent fertilizer nitrogen recovery values on a whole plant basis ranged from 53 to 75%. The proportion of fertilizer recovered in tubers clearly declined with increase in nitrogen supply.

Key-words: Solanum tuberosum, nitrogen fertilization, dry matter accumulation, nitrogen uptake, nitrogen recovery
Introduction

Intensive potato (Solanum tuberosum L.) cultivation demands an adequate supply of nutrients to promote high yield and high quality. The nitrogen sources in the soil comprise the mineral nitrogen initially available in the soil, that which becomes available through mineralization and the external supply of N fertilizer. Soil factors, including water status, temperature, organic matter content and manure use, all impact on the turnover of nitrogen (Jarvis et al. 1996). In addition, average soil mineral nitrogen concentration appears to show substantial variation between years. The complex behaviour of nitrogen in the soil makes it difficult to forecast the amount needed by a crop, and it cannot be predicted at the beginning of the growing season. Since the growing period in northern conditions is short (140-180 days), the application of fertilizer nitrogen must be balanced between the potential yield of the crop and the intended harvest date so as to minimize N losses to the environment (Biemond and Vos 1992, Kuisma 2002). Nitrogen application in excess of the needs of the crop causes overproduction of foliage, resulting in late senescence (Millard and Marshall 1986). Under conditions of high nitrogen supply the risk of nitrate losses from the potato root zone increases, resulting in nitrate contamination to groundwater on the sandy soils typical for potato cultivation (MacDonald et al. 1997). In Finland it is common practice to provide all the N fertilizer at planting, and a split application has been found to be of no benefit to yield compared with a single dose (Kuisma 2002). Moreover, only a very small proportion of the main cropping area receives any input of organic manure.

The official fertilizer recommendations in Finland are based on climatic zone, organic matter content of the soil, potato cultivar and yield forecast. However, the national environmental legislation and support programme contains regulation and base limits for nitrogen application to all major crops. The recommendations for nitrogen fertilization of potatoes are rather low, 60–120 kg N ha⁻¹, according to their exact nitrogen requirements (Kuisma 1995, Mustonen 2004). Farmers are permitted to apply more nitrogen if there is good reason to expect high yields and high quality, to a maximum total application of 120 kg ha⁻¹, comprising both mineral fertilizers and animal manure. Maximum yield is not always attained because of current limits on total nitrogen application rates and limitations related to environmental concerns.

Some potato cultivars appear to be able to take up more nitrogen than others. Firman and Allen (1988) and Firman and Allen (1995) examined the effects of nitrogen fertilizer on potato growth of several contrasting varieties and suggested that indeterminate cultivars may have a smaller nitrogen fertilizer requirement than determinate cultivars. Cultivar differences in nitrogen requirement were related to differences in root systems between cultivars. Similarly Sattelmacher et al. (1990) found differences in nitrogen requirements between two cultivars related to root morphology. Also Zebarth et al. (2003) reported lower nitrogen use efficiency in early maturing cultivars compared with mid-season and late-maturing cultivars. The physiological basis of genotypic variation in nitrogen requirements of potato cultivars is not fully understood.

The objective of this study was to quantify the relationship between nitrogen supply and changes during the season in the accumulation of dry matter and nitrogen. More information was also sought on nitrogen use efficiency and the effect of nitrogen rate on partitioning of dry matter and nitrogen accumulation.

Material and methods

Experiments were conducted in 2000 and 2001 at MTT Agrifood Research Finland, Plant Production Research, Jokioinen, (60° N). The experimental layout for trials harvested at maturity was a split-plot design of four replicate blocks. Nitrogen fertilization was arranged in main plots and potato cultivars in the subplots. The fertilizer treatments were 0, 60 and 120 kg N ha⁻¹. Cultivars Van Gogh and Nicola are widely grown table potato cultivars of similar maturity class. The soil was light sandy soil high in organic matter typical of soils for potato cultivation in
Finland. Previous crop in rotation was spring barley (*Avena sativa* L.).

According to the local practice, the nitrogen, as ammonium nitrate (27% N), at 60 kg N ha\(^{-1}\) and 120 kg N ha\(^{-1}\), was placed in rows 5 cm below and 10 cm to each side of the seed tubers at planting. All plots received potassium sulphate (42% K) and superphosphate (9% P) broadcast before planting at a rate 45 kg P ha\(^{-1}\) and 180 kg K ha\(^{-1}\) based on soil analysis. The trial field was ploughed in the autumn and prepared by fine cultivating to 15 cm three days before planting. Pre-sprouted seed potato was planted with a semi-automatic planter at 5 cm depth and a within-row spacing of 25 cm. The potato was grade 40–45 mm certified seed. The experiments were established on May 18, 2000 and May 21, 2001. A subplot consisted of two rows (1.5 m) by 14 m for each plot, with one extra row acting as a guard row between main plots. Weeds and diseases were controlled using standard cultivation practices for the region and crops were practically free from both. Trials were harvested with a small harvester without haulm killing. No irrigation was applied.

Soil samples were taken shortly before planting to record the amount of residual mineral nitrogen from 0–15 and 15–30 cm depths. Samples were kept frozen until analyzed. Soil water content was determined as weight loss from the samples by drying them overnight at 105 °C. Soil samples were analyzed by extracting with 2 M KCl and using a Scalar Auto-analyser to determine nitrate NO\(_3\)–N and ammonium NH\(_4\)–N. Mineral nitrogen content of soil was determined as the sum of extracted nitrate and ammonium.

Plant dry matter and nitrogen accumulation were determined based on whole plant sampling four times during each growing season. Twelve plants were collected by hand from two rows in each plot and two plants were left as guard plants between sampling dates. Sampling dates were 1) 30 days after emergence (DAE), 2) 45 DAE, 3) 60 DAE and 4) 80 DAE. In 2000 there were no tubers at the first early sampling date 30 days after emergence. At final harvest haulms were cut at the soil surface. Plants were partitioned into tubers and haulms and further divided into leaves and stems. All plant samples were dried overnight at 105 °C for dry matter determination and at 60 °C for nitrogen analysis using a LECO FP 428 automatic analysis system. Potato nitrogen uptake at different harvest dates was calculated from measured values by multiplying dry matter of the tuber yields and above-ground parts by the corresponding nitrogen concentration.

Apparent fertilizer nitrogen recovery in the tubers is a measure of the efficiency of uptake of nitrogen applied as fertilizer. It is defined as: 

\[
\text{ARN} (\%) = \frac{[\text{NU}_N (\text{kg N ha}^{-1}) - \text{NU}_N (\text{kg N ha}^{-1})]}{\text{(fertilizer N applied (kg N ha}^{-1}) \times 100 \text{, where ARN is apparent fertilizer N recovery, NU}_N \text{ is the tuber N content for a given fertilizer N treatment and NU}_N \text{ is the tuber N content for the unfertilized control treatment. In these calculations it is assumed that both control and nitrogen fertilized plots absorbed the same amount of soil nitrogen. A possible source of error is that roots stimulated by fertilizer application may also take up some more nitrogen.}}
\]

The data for total dry matter, foliage dry matter, total content of nitrogen, nitrogen content of foliage and tuber dry matter content were analysed separately for 2000 and 2001. In the analyses, nitrogen fertilisation was considered as a main-plot factor, cultivar as a subplot factor, sampling date after emergence as a repeated measure and replication as a blocking factor. Repeated measurements from the same experimental plot were correlated, which was taken into account in the statistical models through appropriate covariance structures. The statistical model thus was:

\[
y_{ijkl} = \mu + \beta_i + n_j + e_{ij} + c_k + (nc)_{jk} + \delta_{ijk} + d_l + (\beta d)_{il} + (nd)_{jl} + \theta_{qjl} + (cd)_{kil} + (ncd)_{jkl} + \gamma_{ijkl},
\]

where \(\mu\) is constant intercept, \(n_j\), \(c_k\), \((nc)_{jk}\), \(d_l\), \((\beta d)_{il}\), \((nd)_{jl}\), \(\theta_{qjl}\) and \((ncd)_{jkl}\) are fixed main and interaction effects for the nitrogen fertilisation \((n)\), cultivar \((c)\) and sampling date \((d)\). The \(\beta_i\) is the random effect for block \(i\), and \(e_{ij}\) and \(\delta_{ijk}\) are random main plot and subplot error effects, all mutually independent with variances \(\text{var}(\beta_i) = \sigma^2_{\beta}\), \(\text{var}(e_{ij}) = \sigma^2_{e}\) and \(\text{var}(\delta_{ijk}) = \sigma^2_{\delta}\). The \((\beta d)_{ij}\) represents the random time-specific contribution for block \(i\), and \(\theta_{qjl}\) and \(\gamma_{ijkl}\) represent random time-specific main plot and subplot error effects (Gumpertz and Brownie 1993). The harvest at
maturity data (tuber yield, tuber dry matter yield, dry matter content and nitrogen uptake) were recorded only once each year. However, the data from both years were analysed together, so year was considered as the repeated measure in this analysis.

For all the models mentioned above, REML was used as the estimation method and degrees of freedom were calculated using the Kenward-Roger method (Kenward and Roger 1997). The models were fitted using the MIXED procedure of SAS 9.2 (SAS Institute Inc., Cary, NC, USA). Pairwise comparisons were performed using two-sided t-type tests. Model assumptions were checked using appropriate graphs. For the tuber dry matter content in 2000, base-10 logarithmic transformation was applied to the data because of unequal variances on the original scale.

### Results

#### Weather conditions and soil nitrogen availability

Weather data for May – August from the Jokioinen weather station of the Finnish Meteorological Institute are given in Table 1. The mean air temperature during the growing season was 14.3 °C in 2000 and 15.4 °C in 2001, compared with a long-term average of 13.8 °C (Table 1). Precipitation during the growing season was 276 mm in 2000 and 233 mm in 2001, compared with a long-term average (1971–2000) of 252 mm. However precipitation in July 2000 was 30.6 mm higher than the long-term average, whereas the mean temperature in July 2001 was 18.9 °C, which was 2.8 °C higher than normal. As a result, climatic conditions during the early weeks of July were wetter in 2000 and drier and much warmer in 2001 than the long-term average. Dry conditions in combination with above average daily temperatures (19–22 °C) during the first part of July resulted in water stress and retarded growth in 2001. However, good crop growth occurred in 2001 during late July and August when precipitation and temperatures were at the optimal level. More typical growing conditions occurred in 2000 despite the high precipitation in July.

Soil mineral nitrogen at a depth of 30 cm at planting was 13.4 kg NO₃-N ha⁻¹ and 5.2 kg NH₄⁺-N ha⁻¹ in 2000, and 19.3 kg NO₃-N ha⁻¹ and 7.5 kg NH₄⁺-N ha⁻¹ in 2001. Plant nitrogen uptake with no nitrogen fertilization, a crude indicator of soil nitrogen supply, was higher in 2001, at 60 kg N ha⁻¹, compared with 38 kg N ha⁻¹ in 2000. On the basis of soil mineral nitrogen and plant nitrogen uptake in no-nitrogen plots, soil nitrogen supply was 57, 117 and 177 kg N ha⁻¹ in 2000 and 87, 147 and 207 kg N ha⁻¹ in 2001, for the 0, 60 and 120 kg N ha⁻¹ plots, respectively.

### Crop development and nitrogen uptake pattern

The effects of nitrogen level during the season on the plant dry matter are shown in Figure 1a and Figure 2a. The changes during the season in the plant dry matter accumulation showed significant differences between the effects of nitrogen treatments in both years (p < 0.001). Differences between cultivars (p < 0.001) were significant only in 2000, when cultivar Van Gogh had a higher dry matter content than Nicola throughout the season. The highest total dry matter content was generally reached using 120 kg N ha⁻¹. However, the differences between nitrogen levels of 60 and 120 kg N ha⁻¹ were significant only...
at sampling dates 45 DAE ($p < 0.001$) and 60 DAE ($p < 0.01$) in 2000 and during the second part of the growing season at sampling dates 45 DAE ($p = 0.05$) and 60 DAE ($p < 0.01$) in 2001.

The total plant nitrogen accumulation (Fig. 1 b and Fig. 2 b) was significantly increased with nitrogen applications ($p < 0.001$) in both years. The greatest differences between nitrogen levels were noted during the period of rapid haulm growth 40–65 DAE. In 2001 the total plant nitrogen accumulation significantly increased ($p < 0.001$) between in the last two sampling times of the growing period. The opposite effect was found in 2000 when the plant nitrogen uptake decreased at the last
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sampling in August. The differences between years were due to differences in climatic conditions. The difference between cultivars was significant only in 2000 when Van Gogh showed higher ($p < 0.001$) total nitrogen uptake than Nicola. Van Gogh had significantly higher ($p < 0.001$) total plant nitrogen uptake than Nicola at 120 kg N ha$^{-1}$.

The nitrogen treatments strongly influenced the plant haulm dry matter accumulation and the nitrogen accumulation of the haulms to an even greater extent (Figures 1 c–d and Figures 2 c–d). In 2000, except for the first sampling date, nitrogen levels had a significant effect on both dry matter ($p < 0.001$) and nitrogen accumulation of haulms.
(\(p < 0.001\)). In 2001, in addition to other sampling dates, there were also significant differences between nitrogen level 0 and the other nitrogen levels (\(p < 0.001\)) at the sampling date 30 DAE. The dry matter and nitrogen that accumulated in haulms started to decline during the later part of the season and nitrogen was relocated to tubers. The internal relocation of dry matter and the nitrogen from haulms was similar for both cultivars and at all nitrogen levels and was similar in both trials. In 2001 Nicola had higher dry matter content of haulms than Van Gogh at the sampling date 60 DAE (\(p < 0.001\)). However in 2000, Van Gogh had significantly higher dry matter content 30 DAE (\(p < 0.001\)) and 45 DAE (\(p = 0.04\)) and also higher haulm nitrogen content 30 DAE (\(p < 0.001\)). The amount of dry matter and nitrogen accumulation in haulms was substantially higher in 2000 compared with 2001. The differences between years were due to differences in climatic conditions.

In 2000 the effect of nitrogen (Figure 3a) on the tuber dry matter accumulation was significantly different between nitrogen levels 60 days after emergence in early August. Van Gogh had higher tuber dry matter content than Nicola at sampling dates 45 DAE (\(p < 0.001\)), 60 DAE (\(p < 0.001\)) and 80 DAE (\(p < 0.01\)). In 2001 the variation in tuber dry matter accumulation between 60 and 120 kg N ha\(^{-1}\) was small during the first part of the season (Figure 3b) and a significant difference between nitrogen treatments (\(p = 0.02\)) was found only at the last sampling date in August. An opposite reaction of the cultivars was noted when Nicola had higher tuber dry matter content than Van Gogh at the last two sampling times in August. However, differences between cultivars were not statistically significant. The dry matter accumulation in tubers was generally much higher during the 2001 growing period.

**Tuber yield, dry matter and final nitrogen uptake**

Tuber yield generally increased with increasing nitrogen application rate, when tubers were harvested at maturity (Table 2). The main effects of nitrogen (\(p < 0.001\)) and cultivar (\(p < 0.05\)) were statistically significant, but there was no difference between
years in these effects. Cultivars reacted differently between years \((p < 0.001)\), but there was a similar response of cultivars between nitrogen levels \((p = 0.078)\). Non-significant year × nitrogen interaction indicated that nitrogen had a similar effect in both the trials. Van Gogh had significantly higher \((p < 0.001)\) yield than Nicola at the highest nitrogen application level in 2000 and respectively Nicola had significantly higher yield at all three fertilizer levels in 2001 \((0 \text{ kg N ha}^{-1} (p < 0.05), 60 \text{ kg N ha}^{-1} (p < 0.001)\) and \(120 \text{ kg N ha}^{-1} (p < 0.001)\) in 2001).

As for tuber yield, nitrogen application significantly increased the plant dry matter accumulation (Table 2). Differences between cultivars and years were not significant and cultivars did not react differently to nitrogen applications. Statistically significant interactions were recorded for nitrogen × year \((p < 0.01)\) and cultivar × year \((p < 0.01)\). The tuber dry matter accumulation was not significantly different between nitrogen application rates of 60 kg N ha\(^{-1}\) and 120 kg N ha\(^{-1}\) for Nicola in 2000, but was more responsive to nitrogen fertilization in 2001.

Dry matter content in tubers declined with nitrogen fertilizer levels (Table 2). When cultivars were compared, it was significantly lower for the later-maturing Nicola. Dry matter content of tubers was also significantly higher \((p < 0.001)\) in 2001 compared with 2000, as a result of different climatic conditions between years.

The significant effects of nitrogen \((p < 0.001)\) and year \((p < 0.001)\) were found on the plant nitrogen uptake of tubers (Table 2). The main effect of cultivar was not significant, but the interaction between year and cultivar \((p = 0.02)\) indicates that there were differences between cultivars only in 2000. Nitrogen accumulation of tubers was clearly higher in 2001 compared with 2000.

### Efficiency of nitrogen use

Apparent fertilizer nitrogen recovery calculated for both years showed a tendency to decline at the high nitrogen fertilizer application level of 120 kg N ha\(^{-1}\) (Table 3). The proportion of nitrogen recovered found in tubers increased between 80 DAE and the final harvest in 2000 but not in 2001. Recoveries of nitrogen were much lower in 2000 than in the drier

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**Table 2.** Effect of year, nitrogen application level and cultivar on tuber yield, plant dry matter accumulation and nitrogen accumulation in 2000–2001. Adjusted means within each year and treatment not followed by same letter are significantly different at \(p \leq 0.05\).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N-level</th>
<th>Cultivar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Tuber yield, kg/ha(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>29.8(^a)</td>
<td>39.8(^b)</td>
</tr>
<tr>
<td>2001</td>
<td>28.3(^a)</td>
<td>40.7(^b)</td>
</tr>
<tr>
<td>Mean</td>
<td>29.1</td>
<td>40.3</td>
</tr>
<tr>
<td>Dry matter yield, kg/ha(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>7.3(^a)</td>
<td>9.4(^b)</td>
</tr>
<tr>
<td>2001</td>
<td>7.1(^a)</td>
<td>10.1(^b)</td>
</tr>
<tr>
<td>Mean</td>
<td>7.2</td>
<td>9.7</td>
</tr>
<tr>
<td>Dry matter, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>24.5(^a)</td>
<td>23.7(^b)</td>
</tr>
<tr>
<td>2001</td>
<td>25.1(^a)</td>
<td>24.8(^b)</td>
</tr>
<tr>
<td>Mean</td>
<td>24.8</td>
<td>24.2</td>
</tr>
<tr>
<td>N-uptake, kg/ha(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>38.1(^a)</td>
<td>75.3(^b)</td>
</tr>
<tr>
<td>2001</td>
<td>60.4(^a)</td>
<td>98.8(^b)</td>
</tr>
<tr>
<td>Mean</td>
<td>49.3</td>
<td>87.1</td>
</tr>
</tbody>
</table>
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Discussion

In 2001 climatic conditions ranged from near normal to low precipitation in combination with high daily temperatures, resulting in water stress during early July. On the other hand, optimal growth conditions during late July and August occurred in 2001. Differences in climatic conditions represent the normal variation between seasons that typically occurs in this region under non-irrigated conditions. Also many differences in crop reactions were caused by differences in the climatic conditions. The high soil fertility in 2001 is reflected in the higher soil mineral nitrogen in spring and higher soil nitrogen mineralization measured as the total nitrogen uptake of the unfertilized crop, and also the higher plant nitrogen accumulation in 2001 compared with 2000. Therefore, there was a significant effect of year on many traits reported in this study.

Nitrogen supply influences the development of potatoes by increasing the expansion rate of leaves, affecting the total amount of solar radiation intercepted and the partitioning of dry matter within the plant. Nitrogen itself has little effect on the amount of dry matter produced per unit of intercepted radiation (Millard and Marshall 1986). Differences between nitrogen levels in the plant dry matter accumulation were small during the first part of the season. Cultivars had similar genotypic reactions to nitrogen and only minor differences in the characteristics of the cultivars were established. The highest dry matter yield was generally obtained at a nitrogen supply of 120 kg N ha⁻¹. A high nitrogen application rate increased the period of maximum growth and increased the total haulm dry matter accumulation in particular. On the other hand, oversupply of nitrogen causes excessive growth of the foliage, resulting in too large a canopy for optimal tuber growth (Vos and Biemond 1992, Harris 1990). However, nitrogen supply needs to be sufficient to avoid a low level of light interception and reduced photosynthetic capacity. In the report of Allison et al. (1998) it was found that each unit of leaf area index needed a total uptake of 30–50 kg N ha⁻¹.

The official recommendations in Finland for nitrogen fertilizer application are very low (60–120 kg ha⁻¹) compared with the European levels (160–220 kg ha⁻¹) related to higher yield levels than those commonly obtained in Finland. In the short growing period characteristic of Finland, nitrogen levels must balanced between the potential yield and the date of harvest. The results in these experiments indicate that an application of only 60 kg N ha⁻¹ was sufficient to allow rapid ground cover development and so there was no reduction in yield until later in the season when the canopy started to senesce because of the low nitrogen supply. Similar findings regarding changes during the season in the accumulation of dry matter at different nitrogen levels were reported by Mil-

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<tbody>
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<td>N level, kg/ha⁻¹</td>
<td>60</td>
<td>20.2</td>
<td>11.1</td>
<td>52.1</td>
<td>64.2</td>
<td>72.4</td>
<td>75.4</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td>120</td>
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<td>11.1</td>
<td>28.6</td>
<td>47.1</td>
<td>53.0</td>
<td>60.3</td>
<td>45.7</td>
</tr>
<tr>
<td>Cultivar</td>
<td>Van Gogh</td>
<td>24.2</td>
<td>10.9</td>
<td>43.1</td>
<td>54.5</td>
<td>67.3</td>
<td>65.4</td>
<td>53.3</td>
</tr>
<tr>
<td></td>
<td>Nicola</td>
<td>20.4</td>
<td>13.5</td>
<td>37.5</td>
<td>56.7</td>
<td>57.9</td>
<td>70.3</td>
<td>56.5</td>
</tr>
</tbody>
</table>

2001. The average amount of nitrogen left in haulm residues 80 days after emergence was 11–24% of the total plant nitrogen, representing 26–42 kg N ha⁻¹.
lard and Marshall (1986) and Riley (2000). Both cultivars were medium early cultivars and were also of the determinative type of growth, partitioning the dry matter and nitrogen in a similar way into the haulms. Indeterminate varieties take more nitrogen from the soil and the accumulation of dry matter and nitrogen into haulms is greater and can be maintained for longer periods than in early maturing cultivars of the determinate type (Firman and Allen 1989 and Allison et al. 1998).

During early growth stages, potato plants take up nitrate at excessive levels and most of the plant nitrogen is accumulated in haulms (Millard and Marshall 1986, Vos 1999). In this study the nitrogen content of haulms started to decline 45 days after emergence and most of the nitrogen was re-located from haulms to tubers. In 2001 total plant nitrogen increased until late August on account of the high nitrogen supply following the water-stress period during the first part of the season.

Considering the results at maturity, tuber yield, plant dry matter and nitrogen accumulation were related to crop nitrogen supply. Although the high dose of 120 kg N ha\(^{-1}\) significantly increased dry matter accumulation, the profit was not high because dry matter concentration in tubers declined by 2.6% in 2000 and by 1.1% in 2001 between 60 and 120 kg N ha\(^{-1}\) application rates. During the limited growing period dry matter content corresponding with the high nitrogen application rates could not match the dry matter content associated with the lower nitrogen supply before the end of the growing season. The same effect of nitrogen levels on dry matter content has been reported in several European studies (Vos 1997, Riley 2000, and Hagman and Olsson 2006). There were significant interactions between cultivars and years in tuber yield, and between dry matter and nitrogen accumulation. This can be attributed to the differences in rainfall, suggesting that leaching losses may have occurred in July 2000 when rainfall was 30 mm above the long-term average. Also the period of high temperatures and water stress in 2001 may have caused genotypic reaction. Under these conditions Nicola proved to be more resistant to drought than Van Gogh. Dry matter accumulation clearly increased with increasing supply of nitrogen to the crop because nitrogen supply was no longer a limiting factor for dry matter accumulation.

Apparent fertilizer nitrogen recovery was calculated for tubers harvested 80 days after emergence when haulms started to senesce (80–85% of leaf area) and when the plants had reached maturity. Recoveries were lower in the wet year of 2000 than in the dry year of 2001, probably as a result of N leaching occurring during the mid-late season in 2000. The proportion of recovered fertilizer found in tubers clearly declined with increase in the level of the nitrogen supply. The recovery values (53–75%) on a whole plant basis were similar in these experiments to those recorded in field trials conducted by Vos (1997) and Neeteson (1989). In Michigan, Joern and Vitosh (1995) reported lower recovery percentage of fertilizer nitrogen, ranging from 34% for tubers to 52% for the whole crop. In the study of Riley (2000) in Norway, recoveries ranged from 27–56% for tubers of early and semi-early cultivars. Kuisma (2002), in Finland, reported high nitrogen recoveries of 58–99% based on tuber analyses. The quantity of nitrogen left in the soil by crop residues ranged from 12–22% of that applied. This supports conclusions (Allison et al. 1998) that the potato crop does not necessarily leave large nitrogen residues in the soil after harvest.

Large amounts of fertilizer nitrogen represent a risk to quality and particularly to the environment. The results suggest that an application of only 60 kg N ha\(^{-1}\) was sufficient to allow rapid ground cover development and there were relatively small reductions in yield until late in the season compared with when nitrogen was applied at 120 kg N ha\(^{-1}\). The nitrogen was accumulated during the first half of the season in haulms and relocated to tubers in significant amounts in the later part of the season. The results are consistent with previous findings in the region and the official base limits for fertilizer recommendations of 60–120 kg N ha\(^{-1}\) in Finland.
References


Model prediction of frost tolerance as related to winter survival of wheat in Finnish field trials

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The model FROSTOL simulates course of frost tolerance in winter wheat on a daily basis from sowing on as affected by soil temperature (2 cm), snow cover, phenological development, and a genotypic maximum level of frost tolerance (LT50). A series of cultivar trials in Finland was used to evaluate the model’s ability to estimate plant survival in natural field environments during winters with differing weather conditions. Recorded survival was compared with number of intersections between the curves of simulated LT50 and the soil temperature curve for each field. A cumulative stress level (CSL) was calculated based both on number of intersections and FROSTOL simulated stress levels. The correlation between CSL and field recordings was quite low. While the field trials characterize a general ability to stand various types of winter stress, FROSTOL estimates damage caused by the soil temperature regime only. However, FROSTOL simulations seemed to correspond reasonably well to field observations when low temperature was the eventual cause of damage.

Key-words: winter wheat, frost tolerance, phenological development, ice cover, snow mould, winter survival.

Introduction

Among the numerous models simulating winter wheat performance in response to environmental factors (e.g. Semenov and Porter 1995, Rickman et al. 1996, Jamieson et al. 1998), the recently published FROSTOL (Bergjord et al. 2008) is one of very few models that specifically aims at predicting winter survival of the crop. FROSTOL simulates course of frost tolerance, expressed as LT50 (the temperature at which 50% of the plant populations are killed), on a daily (t) time step from sowing onwards as:
Frost tolerance increases (lowering LT50) by hardening (RH) and decreases by dehardening (RD) and stress. Two stress terms are included. One of them is caused by exposure to low temperature (RS). The other one is related to conditions where respiration stress might occur, conditions where the soil is unfrozen and the ground simultaneously covered with snow (RR). Plants in unfrozen soil would have a higher respiration rate than those in frozen soil, and a dense snow cover might, as ice encasement, create more or less anaerobic conditions for respiration and capture of metabolites like CO2, ethanol, and lactate (Andrews and Pomeroy 1979, Gudleifsson 1997).

The functional relationships of the model are all driven by daily measurements of soil temperature (2 cm). One of them (RR) is in addition affected by snow depth, and two (RH and RD) are conditioned by stage of phenological development. Several experiments have demonstrated a reduced ability to harden and an increased liability to dehardening once the plants are fully vernalized and induced to generative development (e.g. Fowler et al. 1996a, 1996b, Mahfoozi et al. 2001a, 2001b, Danyluk et al. 2003, Limin and Fowler 2006). In FROSTOL this is actuated by terminating the ability of the plants to further hardening, and lowering the temperature threshold for dehardening, after vernalization saturation. A more complete description of the model is given by Bergjord et al. (2008).

FROSTOL was optimized and calibrated by data from experiments where the winter wheat plants were grown outdoors in boxes. A cross validation of the model indicated that its parameters were satisfactorily insensitive to variation in winter weather (Bergjord et al. 2008). However, the model has not yet been tested by the use of independent data derived from common field management practices. The objective of the present study was to evaluate the model’s ability to estimate plant survival or death in true field environments during winters with differing weather conditions.

Material and methods

The data used in the present study were recorded from a series of cultivar trials in Finland conducted at six sites in the years 1989/90, 1990/91, and 1991/92 (Hömmö 1994). The locations were: Mietoinen (60°8’N, 21°51’E), Anjalankoski (60°43’N, 26°48’E), Jokioinen (60°49’N, 23°30’E), Pälkäne (61°20’N, 24°13’E), Laukaa (62°20’N, 26°10’E), and Sotkamo (64°06’N, 28°20’E). Each field included 21 different cultivars covering a large range of variation in frost tolerance.

The fields were sown late August and fertilised in autumn according to the normal practice of the area. All cultivars were sown in 1 m rows, completely randomized, and in four replicates. Winter survival was rated by counting number of living plants both in autumn and in spring soon after snow melting. Further information about the field trials is given by Hömmö (1994).

Weather records including minimum, maximum and mean air temperature (1.5 m above ground), amount and form of precipitation, depth of snow cover, relative air humidity, and wind speed were provided for all locations by The Finnish Meteorological Institute, Helsinki. Unfortunately, no recordings of soil temperature in 0–5 cm depth were available, which is a necessary input to the FROSTOL model. To obtain estimates of the soil surface temperature on a daily basis, the Norwegian model SnowFrost (Thorsen and Haugen 2007) was applied. Input data for these simulations were diurnal mean air temperature and daily recordings of snow depth and precipitation for each location and year.

Maximum attainable frost tolerance level (LT50c) of the different cultivars is required to run the FROSTOL model. Pulli et al. (1996) list results from several different methodological tests of frost tolerance for the cultivars included in the Finnish data set. The listed results from an Icelandic test applying a similar method as the one used in the development of FROSTOL were used to estimate an LT50c for the different cultivars. The plants used in the Icelandic test had been hardened at 2 °C for two weeks only before they were tested. Thus,
their internal ranking was shown, but they had not reached their maximum attainable levels of frost tolerance after these two weeks of hardening. To estimate values of LT$_{50c}$ of the applied cultivars, FROSTOL was run with a constant temperature of 2 °C combined with differing levels of LT$_{50c}$ in order to develop a set of curves for the course of hardening (Fig. 1). Data on LT$_{50}$ of each cultivar from the Icelandic test were then used to position the cultivars on one of the fitted curves at 14 days. As a result, the cultivars were grouped in five classes with values of LT$_{50c}$ at –12 °C (four cultivars), –14 °C (eight cultivars), –16 °C (three cultivars), –18 °C (four cultivars), and –22 °C (two cultivars).

Hömmö (1994) grouped the cultivars somewhat differently; with a difference in ranking as expected. Hömmö’s ranking was based on recorded mean winter survival, reflecting the cultivars’ overall abilities to tolerate different kinds of abiotic and biotic winter stress, whereas the above mentioned ranking used in the present study is based on frost tolerance only.

Model simulations were run for each combination of year, location, and level of maximum frost tolerance. The model outputs were thereafter compared with recorded mean survival of the different cultivar classes. The more intersections found between the soil temperature curve and the curve of simulated LT$_{50c}$, the poorer survival of plants was expected. In order to account for these specific critical incidents, and also the impact of more long-term stressful conditions, a simulated cumulative stress level (CSL) throughout the winter was calculated and correlated with recorded survival for each year, location, and cultivar class. The equation of CSL (2) includes two kinds of stress simulated by FROSTOL (RR and RS), which both express daily impairments in LT$_{50}$ due to low temperature and snow cover, respectively, and a factor related to number of incidents when the diurnal mean soil surface temperature got lower than the corresponding simulated LT$_{50}$. This contribution was included simply by multiplying the total number of such incidents per simulation series by a constant, set to 0.05. Thus, CSL during a winter of n days with I number of intersections was calculated as:

\[
\text{CSL} = \sum_{i=1}^{n} (RR+RS)_i + 0.05 \sum_{i=0}^{n} I_i
\]

Fig. 1. Simulated course of LT$_{50c}$ at a constant temperature of 2 °C for cultivars with levels of maximum attainable frost tolerance ranging from –12 to –22 °C.
Table 1. The percentage of winter survival and standard deviation (SD) for the total of 21 winter wheat cultivars from six Finnish locations during 1989/90, 1990/91, and 1991/92. The cultivars are grouped in five classes according to their estimated level of maximum attainable frost tolerance (LT<sub>50</sub>):

<table>
<thead>
<tr>
<th>LT&lt;sub&gt;50&lt;/sub&gt;</th>
<th>Cultivar</th>
<th>Mietoinen 90/91</th>
<th>Jokioinen 90/91</th>
<th>Pälkäne 89/90</th>
<th>Anjalankoski 90/91</th>
<th>Laukaa 89/90</th>
<th>Sotkamo 89/90</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT&lt;sub&gt;50&lt;/sub&gt;: –22 °C</td>
<td>Albidom (RU)</td>
<td>95.6</td>
<td>100</td>
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<td>99.0</td>
<td>72.5</td>
<td>95.2</td>
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<td></td>
<td>Norstar (CAN)</td>
<td>96.5</td>
<td>99.5</td>
<td>65.2</td>
<td>93.8</td>
<td>78.8</td>
<td>88.7</td>
</tr>
<tr>
<td>LT&lt;sub&gt;50&lt;/sub&gt;: –18 °C</td>
<td>Linna (FIN)</td>
<td>99.0</td>
<td>99.7</td>
<td>83.4</td>
<td>97.1</td>
<td>90.0</td>
<td>95.1</td>
</tr>
<tr>
<td></td>
<td>Vakka (FIN)</td>
<td>98.6</td>
<td>100</td>
<td>83.4</td>
<td>99.4</td>
<td>87.5</td>
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<td></td>
<td>Aura (FIN)</td>
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<td>99.8</td>
<td>86.1</td>
<td>98.0</td>
<td>88.8</td>
<td>89.4</td>
</tr>
<tr>
<td></td>
<td>Goertzen (US)</td>
<td>95.6</td>
<td>99.1</td>
<td>16.0</td>
<td>92.8</td>
<td>58.8</td>
<td>84.0</td>
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Results and discussion

The Finnish data set used in this study comprises winters characterized by low temperatures and rather long periods with snow cover, as well as relatively mild winters with short cold spells (Fig. 2). Soil temperatures estimated by SnowFrost seemed reasonable. The temperature stayed at about 0 °C as long as the soil was covered by deep snow, while varying closer to the prevailing air temperature when snow cover was thin or absent (Fig. 2). Wheat winter survival varied considerably between years and locations (Table 1). In five cases, approximately no plant damage was seen in field at springtime (Mietoinen 1990/91 and 1991/92, Jokioinen 1991/92, Anjalankoski 1989/90, and Laukka 1991/92). In the remaining fields, differential levels of winter damage were seen among cultivars. Some snow mould was observed in most of the fields, but the most damaging infections occurred in Laukka 1990/91 and in Sotkamo 1990/91. In Pälkäne 1991/92 and Anjalankoski 1990/91 ice covered the fields unevenly and caused irregular winter survival of plants (Hömmö 1994). As FROSTOL does not account for stress and plant damage caused by snow mould infections and ice cover, these four fields were excluded from further analyses.

Figure 3 shows two selected examples from the Finnish field trials of the simulated course of LT50 for cultivar classes with differing LT50c values. In cases where none of the curves of simulated LT50 were intersected by the soil temperature curve, no frost damage should be expected (Fig. 3A). As number of intersections between an LT50 curve and the temperature curve increased, percent surviving plants from the corresponding cultivar class was expected to decrease. Figure 3B shows an example of a field where cultivars with high frost tolerance (LT50c of −22 and −18 °C) had high levels of survival, while the recordings of cultivars with an LT50c at −12, −14, and −16 °C, were at 42.6, 63.5, and 54.0% surviving plants, respectively (see also Table 1). Comparison between the simulated LT50 curves of the different classes of cultivars and the soil surface temperature showed similar relations with an increasing number of intersections with decreasing frost tolerance (i.e. rising LT50c temperature).

The close relationship between induction of generative development and decrease in frost tolerance provides the phenological module with a strong control of the last gain in frost tolerance during hardening. If the timing of generative induction is estimated too early, the ability of the plants to harden will be terminated too early as well, giving a higher risk of frost damage. Mietoinen 1990/91 and 91/92, and Jokioinen 1991/92 are possible examples of such a situation. According to the FROSTOL simulations for these fields there should have been reduced survival of the cultivars with the lowest frost tolerance. However, hardly any damage was recorded. The discrepancy can be explained by the lack of a photoperiodic factor in the FROSTOL module simulating phenological development. It has been shown that the induction of generative development may be delayed beyond vernalization saturation by the absence of long photoperiods (Slafer and Rawson 1996, Mahfoozi et al. 2001a, 2001b, Danyluk et al. 2003). An experiment performed by Bergjord et al. (2009) indicated that the induction, and consequently the reduced ability to gain and maintain a high level of frost tolerance, was delayed for about one month after vernalization saturation by the absence of long photoperiods. The amount of available data was, however, too scarce to develop a reliable functional relationship between photoperiod and the timing of generative induction in FROSTOL.

The effect on simulated course of frost tolerance of a delay in generative induction by 21 days after vernalization saturation is shown for Mietoinen 1991/92 in Figure 4. This delay gave the plants a longer hardening period and hence a higher level of frost tolerance. In this case, the attained increase in frost tolerance due to later induction of generative development was enough to avoid frost damages when the temperature dropped in early December.

The correlation between simulated CSL and recorded percent surviving plants was low (R² = 0.34), even when FROSTOL was run with a delay in generative induction by about 20 days after vernalization saturation. This low correlation can
Fig. 2. Recorded air temperature and snow depth, and calculated soil surface temperature (SnowFrost, Thorsen and Haugen 2007) at six Finnish locations during the winter 1990/91.
be explained by the fact that FROSTOL estimates frost damage caused by the soil temperature regime only, while winter survival of different wheat cultivars in the Finnish field trials characterize a general ability to stand various types of winter stress. The frequency of fields and cultivar classes with high winter survival was, however, decreasing as the CSL increased (Fig. 5). As Figure 5 shows, the winter wheat did not seem to suffer any serious damage until the CSL increased to levels above eight, as calculated by eq. (2).

Not unexpected, large differences in rate of survival could be seen in the group of fields and cultivar classes which had been exposed to an intermediate stress level, with CSL ranging from eight to twelve (Fig. 5). When a calculated stress level based only on the soil temperature regime reaches
an intermediate level, the extent of occurrence of other stressful abiotic or biotic factors will be highly decisive for the survival rate.

For the three fields Jokioinen 1990/91, Laukaa 1989/90, and Sotkamo 1991/92, FROSTOL simulated less winter damages than what were actually recorded. A closer look at the weather data from these fields suggests that the plants might have experienced more stressful conditions in late winter or early spring than FROSTOL was able to account for. Periods with snow melting followed by low temperatures may have caused either an ice crust on the soil surface, or a more densely compacted snow cover, creating more anaerobic conditions to the plants. Alternate freezing and thawing of the upper soil layer, or desiccation due to irradiative heating of leaves while the roots were still in a frozen soil, are two other possible explanations for lower plant survival than estimated for these fields.

One of the stress factors in FROSTOL is caused by conditions where a largely unfrozen soil is covered by snow (RR). Snow cover is usually considered as beneficial, or even necessary, for winter survival, as it protects plants from being exposed to lethally low temperatures (Belanger et al. 2002). Results from Bergjord et al. (2008) do, however, indicate that a long-lasting snow cover might also have an exhausting effect, causing a reduction of the plants’ frost tolerance, especially if the soil is unfrozen.

Most likely, a wet, dense snow cover will obstruct air flow and cause larger problems to the plants than a dry, loosely compacted snow cover. Gas exchange may be further obstructed if cycles of thawing and freezing cause the formation of ice layers in the snow as water from melting snow again is frozen. However, as the development of the RR equation was based on a limited number of empirical results from field trials (Bergjord et al. 2008), and knowledge of respiration stress during winter is scarce, the RR equation is yet not capable of differentiating between snow covers of differing densities when calculating stress level. Consequently, some over- or under-estimation of stress levels may have occurred. In Laukaa 1991/92 for instance, the high levels of RR calculated in FROSTOL seem to be an overestimate considering the absence of winter damage recorded in this field. Too high levels of RR may also be caused by overestimations of the soil surface temperature, suggesting a higher respiratory activity and hence more stressful conditions to the snow covered plants than what was actually the case.

In addition to the above mentioned probable explanations for the poor correlation, it should be mentioned that the two cultivar classes with LT_{50c} at −18 °C and −16 °C each includes one cultivar (Goertzen and Longbow, respectively, Table 1) which seems to be more susceptible to snow mould infections than the other cultivars of their classes (Hömmö 1994). In years and fields where snow mould infections were registered, their poorer survival hence affected both mean survival of their classes negatively, and consequently the correlation between simulated stress level in FROSTOL and recorded mean survival. Also, the lack of soil temperature recordings and the need for temperature estimation should be considered as a possible source of inaccuracy in these FROSTOL simulations. A small difference between actual and estimated temperature might in some cases not be of any importance. In other cases, when the temperature has been close to the plants’ limits of frost
tolerance, it may make a great difference to the outcome of the simulation.

The results confirm that winter survival is the result of a combination of biotic and abiotic stress factors. As far as we know, no model currently exists that is able to account for all these various factors in winter survival simulations. The performed simulations seemed to correspond reasonably well to field observations when low temperature was the eventual cause of damage [e.g. Sotkamo 1989/90 (Fig. 3B)], and in fields where low temperature incidents during winter or spring did not cause any winter damage [e.g. Anjalankoski 1989/90 (Fig. 3A), Mietoinen 1991/92 with delayed generative induction (Fig. 4B)]. However, as FROSTOL at present only accounts for low temperature damages, it would not be realistic to expect the model to give accurate predictions of the extent of winter damage in all the presented fields and years. Still, it may provide useful information on the probabilities of having winter damage, as shown in Figure 5, and FROSTOL may hence be seen as a first step towards a model of winter survival in winter wheat under Nordic conditions. To improve the model’s applicability, FROSTOL should be further developed to include modules simulating effects of snow moulds and of snow and ice cover densities on plant survival as well.

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