Whole-Crop Cereals for Growing Cattle

Effects of Maturity Stage and Chopping on Intake and Utilisation

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Abstract

The effects of maturity and chopping of whole-crop cereal silage on intake, digestibility, live-weight gain and feeding behaviour of growing cattle were evaluated.

Organic matter digestibility of whole-crop barley and wheat, mainly explained by fibre concentration and digestibility, decreased from the heading stage to the milk stage of maturity. In barley it did not change between the milk and dough stages, but in wheat it increased.

In general, intake was greatest at the dough stage of maturity, probably due to higher dry matter content and lower fibre concentration of the whole-crop silages. Live-weight gain followed the same pattern due to the higher intake.

Chopping increased intake, more so in light steers than in heavy, when whole-crop barley was harvested at dough stage, but not at heading stage. Lower intake of unchopped silage seemed to be caused by long awns affecting light steers more than heavy. Eating rate increased with chopping but rumination time was unaffected.

In conclusion, whole-crop barley and wheat should be harvested at the heading or dough stage of maturity when fed to growing cattle and preferably chopped at dough stage.

Keywords: whole-crop cereal, growing cattle, intake, digestibility, live-weight gain, eating rate, diet selection

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But though the box be gold, yet snuff
Is snuff – so one supposes
Gustaf Fröding

Contents

List of Publications

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

I B.-O. Rustas, J. Bertilsson, K. Martinsson and E. Nadeau (2009). Intake and digestion of whole-crop barley and wheat silages by dairy heifers (manuscript).

II B.-O. Rustas, E. Nadeau and S. Johnsson (2009). Effect of stage of maturity of whole-crop barley on intake and liveweight gain by dairy steers differing in initial live weight. *Grass and Forage Science* 64(3), 227-235.

III B.-O. Rustas, P. Nørgaard, A. R. Jalali and E. Nadeau (2009). Effects of physical form and stage of maturity at harvest of whole-crop barley silage on intake, chewing activity, diet selection and faecal particle size of dairy steers. *Animal* doi: 10.1017/S1751731109990887, published online 24 September 2009.

IV B.-O. Rustas and E. Nadeau. Chopping of whole-crop barley silage improves intake and live-weight gain of young dairy steers (manuscript).

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Abbreviations

AIA	acid insoluble ash
CP	crude protein
DM	dry matter
INDF	indigestible neutral detergent fibre
IVOMD	*in vitro* organic matter digestibility
LW	live weight
LWG	live-weight gain
ME	metabolisable energy
NDF	neutral detergent fibre
OM	organic matter
OMD	organic matter digestibility
sd	standard deviation
sed	standard error of the difference
WCC	whole-crop cereal
WCCS	whole-crop cereal silage
WCBS	whole-crop barley silage

1 Introduction

1.1 Whole-crop cereals

1.1.1 Definition

Whole-crop cereal silage (WCCS) is made from cereal crops harvested before full ripeness and stored under anaerobic conditions. The term whole-crop denotes that grain and stalks (stem and leaf) are harvested and stored in a mix. In principle, any crop where the whole plant is harvested and used could be denoted whole-crop, but the term seems superfluous in crops that usually consist of the whole plant, such as forage grasses and legumes. Silage made from cereals is also denoted with species name, *e.g.* barley silage, but that can be confusing as grain can be harvested and ensiled separately before full ripeness.

1.1.2 Species

Whole-crop cereals (WCC) generally comprise small-grain cereals and hence forage maize is usually not included. Cereal crops such as wheat, barley, oats, triticale, rye, sorghum and rice are all used as whole-crops, but barley and wheat are probably the most common WCC crops worldwide. In Sweden, barley and oats are the most common species used and they are often intercropped with legumes, *e.g.* peas and horse beans (Rondahl, 2007; Nadeau *et al.*, 2009). Both winter and spring varieties of wheat are used for WCC in Sweden but are of minor importance, as are triticale and rye (SJV, 2009a). Barley and oats are the most common cereal crops in northern Sweden and in areas with mixed agriculture and forestry in the south, where the majority of whole-crop cereals are produced. In addition, intercropping with legumes demands a spring-sown variety, which explains the dominance of barley and oats for whole crops in Sweden (SJV, 2009b).

1.1.3 Importance

Whole-crop cereals are minor forage crops in Europe and North America. However, according to Wilkinson & Bolsen (1996) Canada is an exception, with WCC occupying almost one-third of the area used for forage production. Germany, Denmark and the United Kingdom are the only countries in Western Europe with any significant production of WCC (Wilkinson & Stark, 1992). According to official statistics (SJV, 2009a), the harvested area of WCC in pure stands in Sweden was more than 12 000 ha in 2008, which was similar to the area used for forage maize. Another 21 000 ha of mixed cereals, including legumes, were used for whole crops but even so the total harvested area of whole crops is small in comparison with the 860 000 hectares used for grass and clover (SJV, 2009a).

1.1.4 Nutritional composition

The metabolisable energy (ME) content of WCCS is generally considered to be modest, lower than that of grass and maize silage (Table 1). It should be noted that the values in Table 1 are rough. In a review of the literature, Südekum & Arndt (1998) reported ME to be between 9.1 and 10.9 (MJ kg^{-1} DM) for whole-crop wheat, while others have found larger ranges in the ME of WCCS, with somewhat lower and considerably higher values (Adesogan *et al.*, 1998; Givens *et al.*, 2009). However, as shown in Table 1, the ME and crude protein (CP) concentrations generally vary less in WCCS and maize silage than in grass silage, which makes WCCS a comparatively predictable crop.

Table 1. *Metabolisable energy and crude protein concentration in different types of silage (adapted from Wilkinson & Kirilov, 2003)*

Forage	Metabolisable energy MJ kg^{-1} dry matter	Crude protein g kg^{-1} dry matter
Grass silage	8.5-12.0	80-180
Lucerne silage	8.0-10.0	140-220
Maize silage	10.0-12.0	60-120
Whole-crop cereal silage	8.0-10.0	60-120

1.1.5 Role in the production system

In Sweden, WCC are mainly used as a complement to grass and clover, but can be of considerable importance in production systems in which they are used. Whole-crop cereals often serve as nurse crops to facilitate the establishment of leys with grass and clover and they can also serve as buffer crops to compensate for poor grass harvests. The flexibility is probably the main advantage when using cereal crops for forage production. From a pure stand of cereal, either grain or forage can be harvested. The decision on what to produce can be made over a rather large timeframe, as WCC can be harvested at a wide range of stages during growth, from well before ear emergence until the beginning of ripeness.

WCC harvested at any stage of maturity can be fed as the sole forage to growing cattle. Hence, the flexibility of WCC in the crop production system can be fully utilised when WCCS is used for growing cattle. WCC are characterised by high intake when fed to cattle (Keady, 2005) which might compensate for their modest energy content.

1.2 Maturity of cereals

The characteristics of WCC, as of any forage crop, change with maturation. Therefore in order to relate any animal response to time of harvest, a distinct description of stage of maturity of the crop at harvest is necessary.

A decimal code for the growth stage of cereals was introduced by Zadoks *et al.* (1974), while Tottman (1987) presented an illustrated version of the same code. The principal growth stages from germination until ripening and some of the secondary growth stages from full earing through the dough development stage are presented in Table 2. When applied to a crop, any growth stage value should be interpreted as when half the plants in the crop have reached that growth stage. Code 59 is equivalent to full earing or the heading stage and is often used as a reference as it is an easy stage to identify. Zadoks *et al.* (1974), when designing the growth scale, applied the principle that the growth stages must be easily distinguishable, even for a person with little technical training. However, the growth stage determined in the field is a subjective evaluation and hence comparisons within and between studies based on growth stages are not fully compatible. Another way to express the stage of maturity is by dry matter (DM) content, which is positively correlated to stage of growth but can vary widely with growth site and variety (Harvey, 1992). Several studies use the time after some distinguishable growth stage, *e.g.* crop emergence, awn tip appearance (code 49) or the heading stage (code 59) to describe maturation. Time is undeniably an objective measurement but since the development of crops depends heavily on growing conditions (Hay & Porter, 2006), *i.e.* temperature, precipitation and solar radiation, it can be difficult to use time in comparisons between studies. Growing degree days (or thermal time), where temperature and time are combined to one expression, have been used to describe maturation in WCC (Baron *et al.*, 1992; Ruiter *et al.*, 2004; Wallsten, 2008) and seem to be a promising descriptor.

Table 2. *Principal and secondary growth stages of cereals. Adopted from Zadoks et al. (1974)*

Principal growth stages		Secondary growth stages	
Digit code	Description	Digit code	Description
0	Germination		
1	Seedling growth		
2	Tillering		
3	Stem elongation		
4	Booting		
5	Inflorescence emergence	59	Emergence of inflorescence completed
6	Anthesis		
7	Milk development	73	Early milk
		75	Medium milk
		77	Late milk
8	Dough development	83	Early dough
		85	Soft dough
		87	Hard dough
9	Ripening		

1.3 Yield and composition of whole-crop cereals

1.3.1 Yield and morphological changes in relation to growth

The yield and nutritional value of WCC are determined by the quantitative and qualitative characteristics of the morphological entities of the cereal crop and these characteristics change during growth. The proportions of the different plant parts change during crop growth, as exemplified in Figure 1, and at early stages of maturity the proportion of stem increases relative to that of leaf (Cherney & Marten, 1982b; Südekum *et al.*, 1991b). After ear emergence and onwards, the proportion of stalk (leaf and stem) declines (Figure 1) as the ear gathers weight due to grain filling. The increasing weight proportion of the ear in the whole plant is further enhanced by the declining mass of leaves and stems (Südekum *et al.*, 1991b; Garnsworthy & Stokes, 1993; Mannerkorpi & Taube, 1995). Juskiw *et al.* (2000) also found leaf biomass to decline with maturity but found variable responses in stem biomass, from increasing to constant and declining, in whole crops from different cereal mixtures. They attributed changes in stem and leaf biomass to remobilisation and redistribution of leaf and stem reserves to the filling grain.

1.3.2 Chemical changes in relation to growth

The DM concentration increases with advancing stage of maturity in WCC (Helsel & Thomas, 1987; Khorasani *et al.*, 1997; Adesogan *et al.*, 1998), with Khorasani *et al.* (1997) reporting a more rapid increase during the three weeks prior to dough stage.

The fibre concentration increases in both stems and leaves during growth (Cherney & Marten, 1982b). The fibre concentration also increases in the ear (Cherney & Marten, 1982b) and in the whole crop (Cherney & Marten, 1982a; Khorasani *et al.*, 1997) before grain filling starts, but thereafter it decreases in the ear (Cherney & Marten, 1982b) and generally decreases in the whole crop (Cherney & Marten, 1982a; Garnsworthy & Stokes, 1993; Ashbell *et al.*, 1997; Khorasani *et al.*, 1997; Adesogan *et al.*, 1998; Crovetto *et al.*, 1998; Nadeau, 2007), although it also has been reported to increase (Helsel & Thomas, 1987; Hargreaves *et al.*, 2009).

The CP concentration is highest in the leaves, lowest in the stem and intermediate in the ear of WCC (Cherney & Marten, 1982b; Südekum *et al.*, 1991b). The CP concentration decreases at a higher rate in the leaves than in the stems and stays rather constant in the ear during maturation (Cherney & Marten, 1982b; Südekum *et al.*, 1991b). The resulting CP concentration of the whole crop is generally a moderately decreasing trend after the heading stage of maturity (Helsel & Thomas, 1987; Komprda & Dolezal, 1996; Khorasani *et al.*, 1997; Filya, 2003; Nadeau, 2007).

The concentration of water-soluble carbohydrates (WSC) decreases with maturity and starch concentration increases as grain filling proceeds in WCC (Bergen et al., 1991; Adesogan et al., 1998; Nadeau, 2007; Hargreaves et al., 2009).

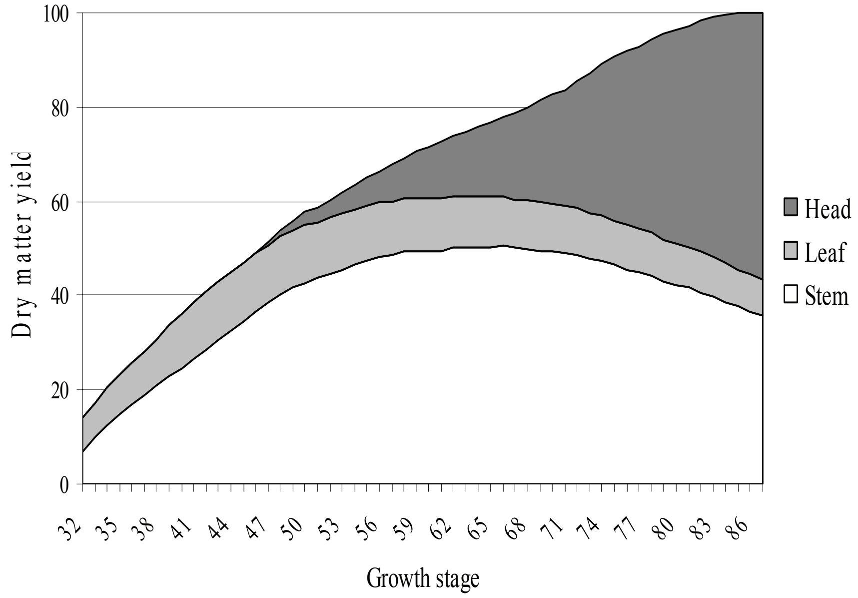

Figure 1. Changes of dry matter yield of stem, leaf and ear of whole-crop wheat during growth from the beginning of stem elongation (growth stage 32 according to Zadoks *et al.,* 1974) until the end of dough stage of maturity (growth stage 87). Modified from Südekum *et al.* (1991).

1.3.3 Changes in digestibility in relation to growth

The digestibility of WCC decreases with maturation. Until the beginning of grain filling, the decreasing digestibility of WCC is mainly due to the decreasing digestibility of the leaf and stem fractions. The stem decreases more in digestibility than the leaf (Südekum *et al.*, 1991b), probably due to a larger decrease in the digestion rate of the cell walls in stems compared with leaves (Cherney *et al.*, 1983). Grain filling increases the digestibility of the ear and its proportion of the whole crop, which counteracts the decreasing digestibility of the stalk. As a result, the decrease in digestibility generally levels off during grain filling (Cherney & Marten, 1982a; Garnsworthy & Stokes, 1993) and might even increase when the grain proportion becomes substantial, *e.g.* at dough stage (Helsel & Thomas, 1987; Ben-Ghedalia *et al.*, 1995; Crovetto *et al.*, 1998).

1.4 Issues

1.4.1 Digestibility

The decision on when to harvest WCC mainly concerns issues directly related to the harvested crop, including crop yield, conditions for conservation, nutritional value and feed intake by the producing animals. Time of harvest might also affect the cropping system, *i.e.* the time available for autumn cultivation and sowing of new crops or the time available for an undersown crop to re-grow and hence its potential yield and quality. However, recommendations on when to harvest WCC have generally focused on digestibility and crop yield.

Sotola (1937) recommended harvest at the dough stage of maturity to optimise nutrient yield. However, that recommendation was based on crops harvested as hay, with the potential risk of grain losses at later stages of maturity, and the greatest energy yield was actually found at full ripeness. Kristensen (1992), referring to results from Denmark, argued that whole-crop wheat and barley should be harvested at the soft dough stage of maturity, but not later, as digestibility decreases after this stage. However, Mannerkorpi & Brandt (1995) found no decrease in organic matter (OM) digestibility between growth stages 83 and 86 and only a slight decrease at stage 91 in whole-crop barley. Mannerkorpi & Brandt (1993) also found a modest linear decline in digestibility of whole-crop wheat from the middle of the milk stage to the transition between the dough and ripening stages. Südekum & Arndt (1998) concluded from a literature review that the optimum harvesting time for WCC is between the beginning and end of the dough stage. O'Kiely (2006), reviewing Irish results, also claimed that harvest should take place between the early dough and hard dough stages of maturity, corresponding to a DM content between approximately 350 and 550 g kg^{-1}. Harvesting of whole-crop wheat at DM contents up to 700 g kg^{-1} (growth stage 87) has been reported in British studies (Jackson *et al.*, 2004). However, digestibility may be depressed at high DM contents, mainly due to low starch digestibility (Abdalla *et al.*, 1999).

Experiences from research with whole-crop cereals grown in Sweden and at Nordic latitudes are limited. However, contradictory to most recommendations, Pettersson (1995) suggested harvesting one week after heading of whole-crop barley and oats grown in the north of Sweden due to declining digestibility of the crops. A faster decrease in the digestibility of WCC at higher latitudes has also been reported for other forages (Deinum *et al.*, 1981). However, Nadeau (2007) reported no decrease in *in vitro* digestibility between the milk and dough stages of maturity of whole-crop barley and oats in a study in south-west Sweden, while Tuvesson (1997) found only a minor decrease in *in vitro* digestibility of whole-crop wheat between the early milk to late dough stages of maturity in southern Sweden.

Predicting the nutritive value of WCC for cattle using i*n vitro* digestibility, as reported by Tuvesson (1997) and Nadeau (2007), or *in vivo* digestibility of sheep, as reported by Pettersson (1995), might not be relevant. In general, cattle digest poor-quality forages more efficiently than sheep (Aerts et al., 1984) but sheep digest grain better than cattle due to their superiority in disrupting whole grains by chewing and possibly also to their smaller omasal orifice, which might reduce the outflow of whole grains from the rumen compared with cattle (McDonald *et al.*, 1995). Results from direct comparisons between the species with WCCS are conflicting. Südekum *et al.* (1995) found greater OM digestibility of whole-crop wheat in cattle than in sheep, whereas Kirchgessner *et al.* (1989) found the opposite for whole-crop wheat and whole-crop barley. When fed the same whole-crop wheat, starch digestion is reported to be considerably lower in dairy cows (Sutton *et al.*, 1994) than in sheep (Adesogan *et al.*, 1998) and Adesogan *et al.* (1998) questioned the use of sheep as a model for whole-crop wheat digestion in cows. Similarly, *in vitro* digestibility does not take into account restrictions in starch digestibility.

The inconsistent findings from the few investigations carried out in Sweden clearly call for clarification of the effect of maturity on the quality of WCC grown under Swedish conditions. There is also a general interest in determining the effects of maturity on digestibility in cattle, as the majority of reported evaluations have used sheep or *in vitro* methods and, as mentioned above, the results from these evaluations might not be applicable in cattle feeding.

1.4.2 Intake and animal performance

Animal performance depends on the intake of digestible nutrients and, as reviewed by Mertens (1994), intake generally accounts for twice as much variability in digestible DM intake as does digestibility. However, intake is not often brought up as an important issue in the discussion of optimum harvest of WCC. The increase in DM content (Dulphy & VanOs, 1996) and the frequently observed decrease in fibre concentration (Mertens, 1994) with maturation are expected to affect intake of WCC by cattle. However, inconsistent responses to WCC maturity in terms of feed intake by growing cattle have been reported, with intake increased (Südekum *et al.*, 1992; O'Kiely & Moloney, 1995) or unaffected (McCullough & Sisk, 1967; Oltjen & Bolsen, 1980; Rojas & Catrileo, 2000) by maturation. Intake of WCC can also be negatively affected by the presence of awns (Bolsen *et al.*, 1976; Christensen *et al.*, 1977), which are bristly and scabrous entities attached to the grain (Laca *et al.*, 2001). Any effect of awns may depend on the maturity of the crop, as the awns seem softer at earlier stages of maturity.

Harvesting technique can also affect intake of WCCS. Harvesting the crop as large bales, which is common in Sweden, results in considerably larger particle size than with precision chopping, which is the predominant harvesting technique in reported studies. Larger forage particle size decreases feed intake in forage crops of grass (Deswysen & Vanbelle, 1978) and legumes (Jaster & Murphy, 1983), especially when harvested at late stages of maturity (Ingvartsen, 1994). A larger forage particle size increases chewing time, mainly through the need for chewing activity during ingestion (Nørgaard, 2003). Stage of maturity of forages also affects chewing activity, as more mature forages are generally more resistant to physical breakdown (Perez-Barberia & Gordon, 1998). Increased chewing during ingestion could decrease eating rate and restrict the time available for rumination, which could limit feed intake (McLeod & Smith, 1989; Teller *et al.*, 1993) The major role of rumination is to reduce the particle size of the rumen contents, thereby making it possible for the undigested particles to escape from the rumen. The efficiency and duration of rumination can therefore affect feed intake (Deswysen & Vanbelle, 1978; Welch, 1982). Soita *et al.* (2002) compared precision-chopped whole-crop barley silage (19 mm) with even shorter chopping but no comparisons between precision chopped and longer WCCS have been reported.

The effects of maturity and forage particle size and their potential interactions on the intake of WCCS when fed to growing cattle clearly need more attention, as intake is crucially important for production responses.

2 Objectives

The overall objective of this thesis was to evaluate the effects of maturity and chopping of whole-crop cereals on their feed value for growing cattle. Specific objectives were to evaluate:

- The effect of stage of maturity at harvest of whole-crop cereals on digestibility, feed intake and live-weight gain when fed to growing cattle
- The effect of chopping and its possible interaction with maturity on chewing behaviour, diet selection, feed intake and live-weight gain by growing cattle

3 Materials and methods

3.1 Whole-crop cereal silages

3.1.1 Crops

Barley (*Hordeum distichum* L.; cv. Kinnan, in Skara and cv. Filippa, in Uppsala) was used in all studies and wheat (*Triticum aestivum* L., cv. Olevin) was used in one (Paper I). The barley crops in Papers II–IV and one of the barley crops in Paper I were grown at the Götala research station, outside Skara in south-west Sweden. The barley crops at Skara were grown on different fields but the dominant soil type was sandy loam with a minor content of organic matter. The wheat and one of the barley crops in Paper I were grown in Uppsala, on clay loam soils with an organic matter content of approximately 5%.

All the crops were grown with common practices used for grain production and none of the crops was undersown with any crop.

3.1.2 Harvest

In all crops, maturity was estimated according to the growth stage code developed by Zadoks *et al.* (1974). Stage of maturity was assessed by the same individual for crops harvested near Skara (Papers II–IV and one of the barleys in Paper I) and by another individual for the crops harvested near Uppsala (Paper I). The crops were harvested at the heading stage of maturity, growth stage 59 (GS 59) in late June in Papers I and III. The barley crop of year 2 in Paper II was also harvested at heading and the results are reported in Rustas *et al.* (2008). The crops were harvested at the milk stage of maturity in Papers I and II and at the dough stage of maturity in

Papers I–IV. The number of days after heading at which the milk stage and dough stage harvests occurred is presented in Figure 2.

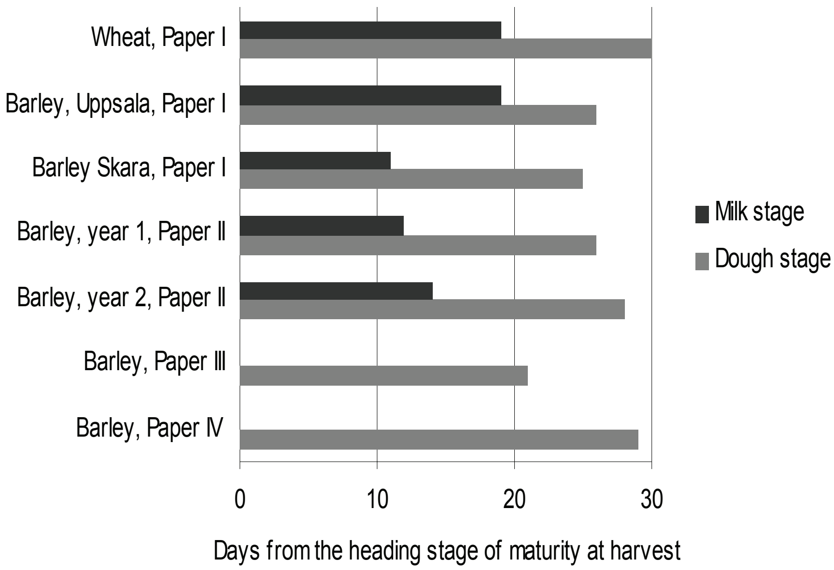

Figure 2. Days past the heading stage of maturity for whole-crop cereals harvested at the milk and at the dough stage of maturity.

All crops were cut with mower conditioners, similar in construction but with different makes and models for the harvests in Skara and Uppsala. To even out differences in DM content between stages of maturity in the standing crop, wilting was done when the weather was suitable.

The crops were round-baled in Papers I, III and IV. Baling machines producing bales with hard cores were used on all occasions and were of the same make and model in Papers I and IV but of a different make in Paper III. The crops used in Paper II were precision-chopped at harvest with the same precision chop forage wagon that was used for chopping the round bales before feeding in Papers III and IV.

Loss of grain was estimated at the harvests in Skara by counting the number of grains left on the ground after each harvesting operation. This was not done in Uppsala.

3.1.3 Ensiling and storage stability

All crops were ensiled and additives were used on all occasions. Salt-based additives were used in all experiments except one of the experimental years in Paper II, when an acid-based additive was used.

Storage stability during the feed-out period was generally good. No sign of aerobic deterioration was observed in the round bale silages. Aerobic stability of the WCBS used in Paper III was studied (Eklund, 2006), mainly to investigate whether chopping before feeding altered the stability. No differences in temperature changes were detected either due to chopping or due to maturity. The chopped crops were ensiled in silos with comparatively large surfaces in relation to the daily amount taken from the silos. Small problems with heat production were occasionally observed at the side of the silos, but this was not thought to affect the experiment as any feed that was suspected to be damaged was thrown away.

3.1.4 Analysis of chemical composition

All chemical analyses of feed were performed at Kungsängen Research Laboratory, Swedish University of Agricultural Sciences, Uppsala. References to the analyses can be found in Paper II and only some comments are made here.

In vitro OM digestibility (IVOMD) was analysed by the standard method used for estimating digestibility in forages of grass and clover in Sweden. During the analysis, 0.5 g of feed was incubated with 1 mL rumen fluid and 49 mL of buffer solution for 96 hours (Lindgren, 1979).

The NDF concentration was analysed with α-amylase, which is essential for removing starch from the sample (Mertens *et al.*, 2002).

Indigestible NDF (INDF) was determined *in situ* on gross samples of the silages in Papers II and IV and on period samples in Paper III by the method used in the Nordic feed evaluation system NorFor. Sample-filled polyester bags with a pore size of 35 microns were incubated for 288 h in the rumen of two dry cows fed a standard hay diet (NorFor, 2007).

3.2 Animals

The heifers used in Paper I were of the breed Swedish Red and were replacements for the dairy herd at Kungsängen Research Centre in Uppsala. The steers used in the experiments at Götala research station originated from several herds in central Sweden. The steers used in Paper III were all Swedish Red. In Papers II and IV, approximately half the animals were Swedish Red and the other half Swedish Holstein, a proportion that roughly corresponds to the present relationship between the two breeds in the Swedish dairy cow population (SvenskMjölk, 2008).

3.3 Housing

In the experiments in Papers I and III the animals were housed in tie stalls and fed individually, whereas they were housed in pens in Papers II and IV. The pens housing light steers had straw bedding and solid concrete floors at the manger, while the pens housing heavy steers had slatted floors.

3.4 Digestibility

In vivo digestibility was determined by total faecal collection in Paper I. Digestibility results were not included in Paper III but using grab samples taken in that experiment, OM digestibility was estimated afterwards by using acid-insoluble ash (AIA) as an internal marker (Kamyar Mogodiniyai Kasmaei, unpublished data). The concentration of acid-insoluble ash was analysed in feeds, orts and faecal samples using the method with 2N HCl described by Van Keulen & Young (1977). Digestibility of the WCCS was calculated by assuming the OM digestibility of soybean meal to be 0.9 according to Spörndly (2003).

3.5 Estimation of energy value

In an attempt to relate the metabolisable energy (ME, MJ kg^{-1} DM) of the WCCS in the studies to that of other forages, the digestibility and ME for sheep were estimated as follows. The *in vivo* OM digestibility (OMD, g kg^{-1}) for heifers was estimated from the *in vitro* OM digestibility (IVOMD, g kg^{-1}) according to the relationship from Paper I (OMD = 1.02IVOMD-166). From the calculated OMD for heifers, the OMD for sheep at maintenance level was then calculated according to the relationship presented by Lindgren (1981) comparing digestion in cows and sheep: $OMD_{cow} = 0.69\ OMD_{sheep} - 11\ L + 225$, where L represents the level of feeding for cows expressed as multiples of maintenance feeding level. In Paper 1, L for the heifers was equivalent to 2. Metabolisable energy was calculated by the relationship between digestible OM in the DM (DOMD), estimated in sheep at maintenance feeding level, and ME according to Givens *et al.* (2009), where ME (MJ kg^{-1}DM) = 0.0156DOMD.

3.6 Live weight, live-weight gain and feed conversion

Animals were weighed continuously in each experiment for calculations of intake in relation to body weight. Live-weight gain (LWG) was calculated from initial and final weights in Papers II and IV, recorded on two or three consecutive days. Feed conversion ratio (kg feed kg^{-1} LWG) was calculated as a measure of feed efficiency.

3.7 Analysis of data

The statistical analyses in each paper were carried out using the computer programs SAS 9.1 (SAS system for Windows, release 9.1, SAS Institute Inc., Cary, NC, USA) and Minitab 15 (Minitab Inc., State College, PA, USA). The Mixed model of SAS was preferred in the analysis of variance, as it is considered to be better when data are unbalanced. Minitab was used in regression and correlation analyses due to it being easier to handle than SAS.

As a complement to the results in Papers I-IV, treatment means from the experiments in the Papers, complemented with some more data, were used in an attempt to describe relationships within the data. Pearson's correlations, partial correlations and simple regression were used to describe relationships between chemical composition variables of the WCCS and relationships between chemical composition and intake variables of WCCS. In total, eight crops were included in the analyses, three from Paper I, two from Paper II (including the harvest at heading stage of year 2 described in Rustas *et al.*, 2008), and the chopped whole-crop barley silages from Papers III and IV and from Rustas *et al.* (2003). Each crop was harvested at one, two or three stages of maturity, making in total 18 silages, 5 harvested at heading, 5 at milk stage and 8 harvested at the dough stage of maturity. Of these 18 silages, there were intake data on 5 silages for light and heavy steers (Paper II, including Rustas *et al.*, 2008 and an unpublished study with light steers), on 2 silages for light steers only (Paper IV and Rustas *et al.*, 2003), on 2 silages for heavy steers only (Paper III) and on 9 silages for heifers (Paper I).

Partial correlations were calculated to remove the effect of other potentially interfering variables when comparing two variables. This was done by the procedure of Minitab 15 (Minitab Inc., State College, PA, USA). The two variables of interest were separately regressed on the variable for which the effect was being adjusted. The partial correlation was the Pearson's correlation for the residuals of these two regression analyses.

The effect of treatments on digestibility in the experiment described in Paper III was analysed according to the model with which the intake data were analysed in that paper.

4 Results

4.1 Whole-crop cereals and silages

4.1.1 Harvested yield and losses

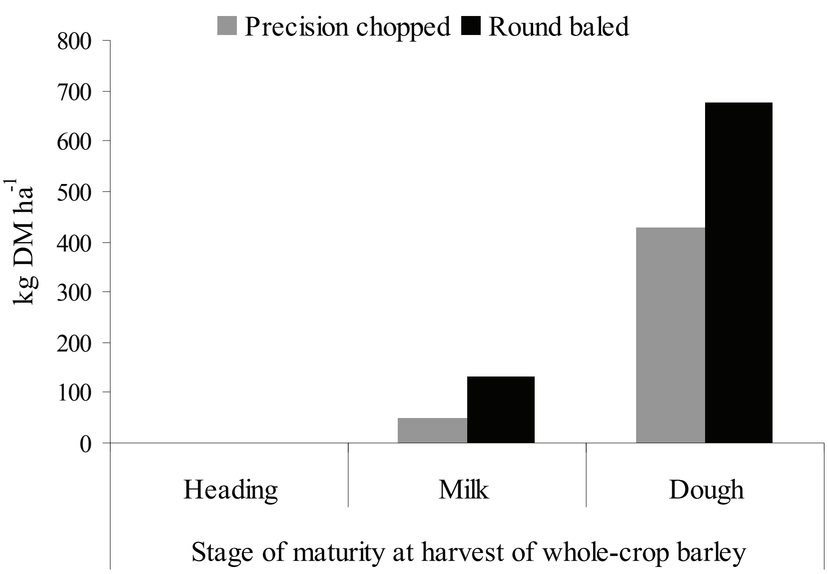

Figure 3. Grain losses at harvest (kg dry matter ha^{-1}) of whole-crop barley averaged over two years. Crops were cut with a mower conditioner and either collected with a precision chopping forage wagon or round baled.

The harvested yield of whole-crop barley was estimated in Paper II and at the heading, milk and dough stages it was (tonnes ha^{-1}) 4.6, 6.5 and 9.2 respectively in 2003 and 5.2, 5.8 and 8.3 in 2004. The head proportion (DM) of the whole crops ranged from 0.21 to 0.25 at the heading stage, from 0.34 to 0.37 at the milk stage and from 0.55 to 0.60 at the dough stage of maturity. Grain losses were zero at the heading stage and increased from the milk to dough stages according to Figure 3. Grain losses were higher when crops were harvested as round bales compared with precision chopping.

4.1.2 Chemical composition of whole-crop cereal silages

The range in DM concentration of the WCCS studied was 235-430 g kg^{-1} FW and the range of other components (g kg^{-1} DM) was: 52-91 for ash, 67-130 for CP, 5-80 for sugar, 6-190 for starch, 431-547 for NDF and 40-61 for lignin. The range in concentration of fermentation products (g kg^{-1} DM) was: 12-115 for lactic acid, 5-25 for acetic acid, 0.3-1.2 for butyric acid,

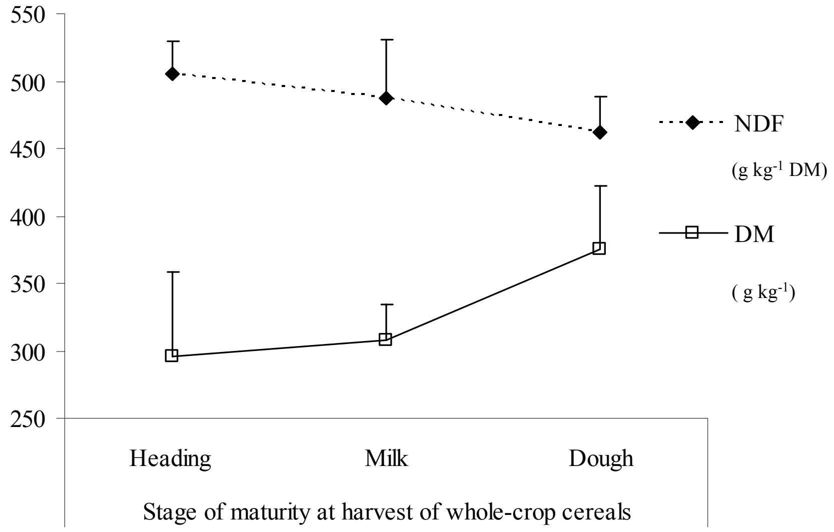

Figure 4. Concentrations of dry matter (DM) and neutral detergent fibre (NDF) in whole-crop cereals silages. Averages from experimental means and standard deviation of the averages (T-bars). Heading: n=5, Milk stage: n=5, Dough stage: n=7.

0.9-2.2 for propionic acid and 2.3-16.0 for ethanol. Ammonia nitrogen (g kg^{-1} total N) ranged between 54 and 121.

The average composition of the silages in relation to stage of maturity is presented in Figure 4 (DM, NDF), Figure 5 (starch, CP, lignin) and Table 3 (fermentation products). The average concentration of sugar (free glucose and free sucrose, g kg^{-1} DM) was 30 (sd 24.1) at heading, 53 (sd 20.3) at the milk stage and 23 (sd 12.4) at the dough stage of maturity.

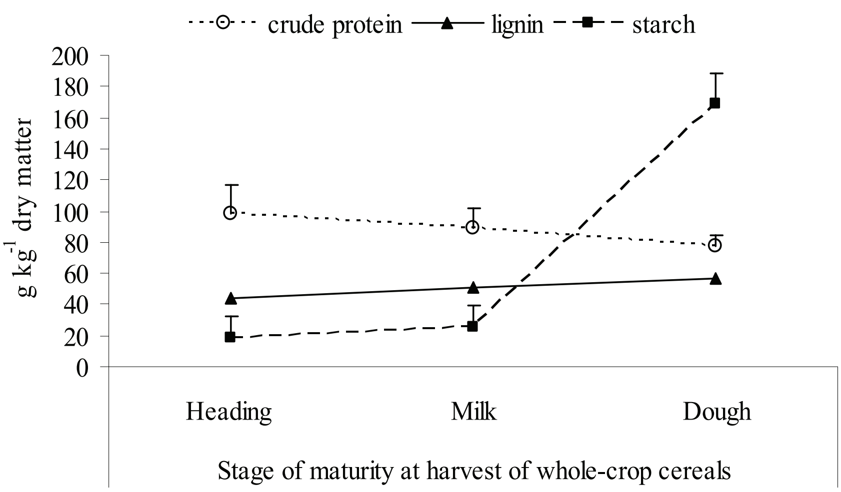

Figure 5. Concentrations of crude protein (CP), lignin and starch (g kg^{-1} dry matter) in whole-crop cereal silages of barley and wheat. Averages from experimental means and standard deviation of the averages (T-bars). Heading: n=5, Milk stage: n=5, Dough stage: n=7.

The DM content increased with maturity and the variation within maturity stage was larger at the heading and dough stages than at the milk stage (Figure 4). The large variation at the heading stage was due to pre-wilting of some crops and not others (Papers I and III), while the large variation at the dough stage was mainly due to differences in weather conditions during harvest (two crops were affected by drizzle (Paper II, year 1 and Paper IV) and one by dew (Paper II, year 2)). There was a linear relationship between DM content of the silages from unwilted crops and days past the heading stage at harvest (Figure 6).

Table 3. Fermentation characteristics of the silages used in the studies. Averages from experimental means and standard deviation of the averages in brackets. All values, except for pH., in g kg^{-1} DM unless stated otherwise.

	Stage of maturity of whole-crop cereals		
	Heading [1]	Milk stage	Dough stage
Dry matter, g kg^{-1}	28.8 (6.29)	29.9 (2.12)	36.6 (4.97)
pH	4.1 (0.32)	4.0 (0.48)	4.3 (0.60)
Lactic acid	74.7 (30.78)	65.9 (33.19)	45.1 (21.39)
Acetic acid	17.1 (5.30)	12.6 (1.67)	8.3 (3.86)
Butyric acid	0.6 (0.19)	0.6 (0.22)	0.6 (0.32)
Propionic acid	1.3 (0.35)	1.5 (0.37)	1.5 (0.50)
Ethanol	6.9 (2.86)	5.0 (5.53)	5.3 (3.94)
NH_3-N, g kg^{-1} N	82.0 (13.64)	82.4 (8.85)	99.1 (25.22)

[1]Heading: n=5, Milk stage: n=5, Dough stage: n=7

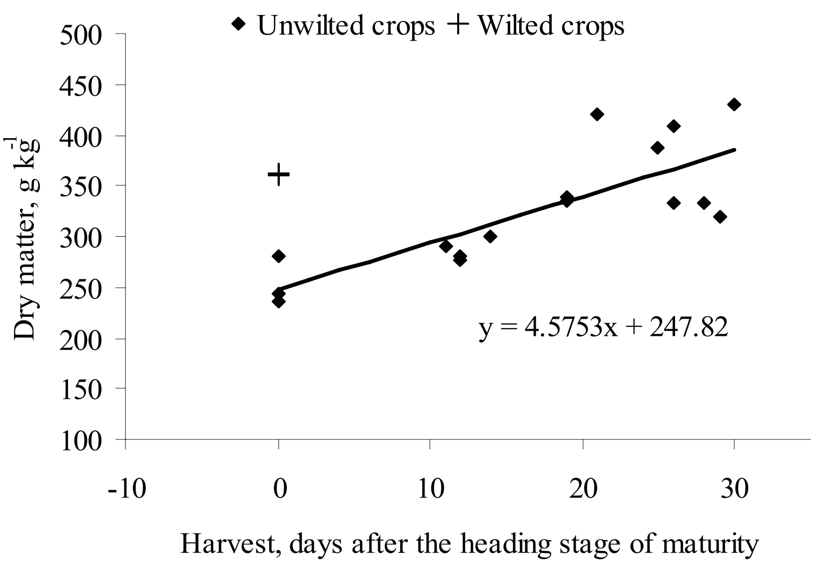

Figure 6. Relation between dry matter content and harvest days past the heading stage of maturity of whole-crop cereal silages from barley and wheat.

4.2 Digestibility

4.2.1 *In vitro* and *in situ* digestibility

The IVOMD of the WCCS ranged from 712 to 840 g kg^{-1} OM and its relationship to maturity is presented in Figure 7. There was a negative linear relationship between INDF and IVOMD and a negative relationship with a similar coefficient of slope between undigested NDF *in vivo* and IVOMD (Figure 8). The IVOMD was negatively (-0.83) and the INDF concentration positively (0.84) correlated with the lignin concentration of the WCCS.

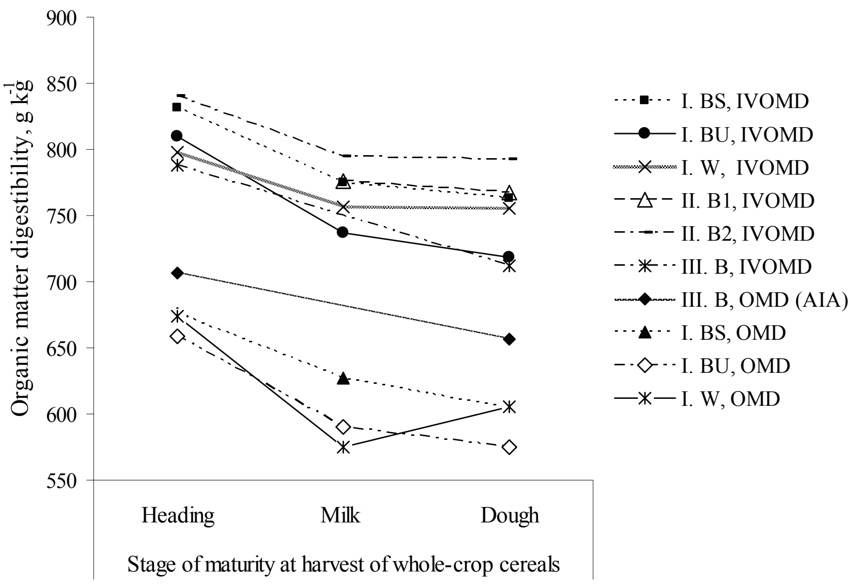

Figure 7. *In vitro* organic matter digestibility (IVOMD), determined after 96 h incubation in buffered rumen fluid, and *in vivo* organic matter digestibility (OMD) determined in heifers by total faecal collection or in steers by the use of acid insoluble ash (AIA) as a marker. Legends refer to the papers in the thesis (I-III). Abbreviations: B = barley, W = wheat, S = grown in Skara, U = grown in Uppsala, 1 = experimental year 1, 2 = experimental year 2.

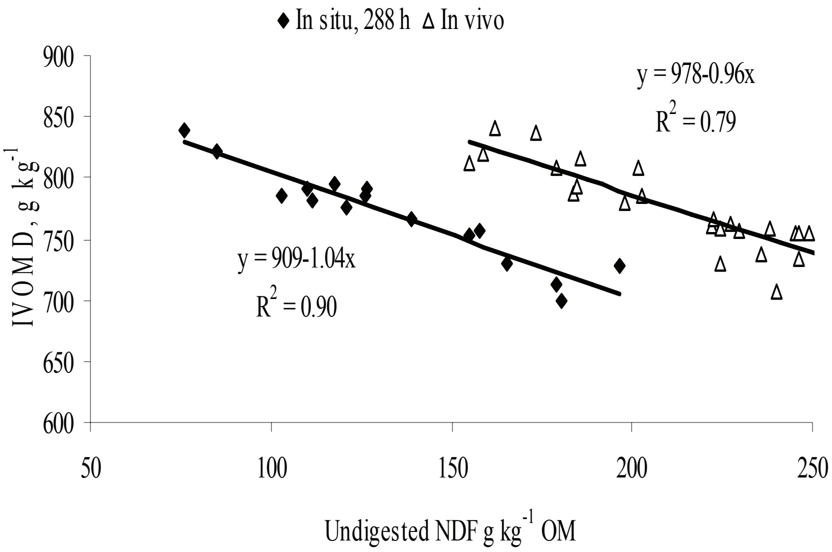

Figure 8.In vitro organic matter digestibility (IVOMD) of whole-crop cereal silages from barley and wheat and its relation to undigested neutral detergent fibre (NDF) after 288 h in situ rumen incubation (indigestible NDF) and in vivo undigested NDF in dairy heifers.

4.2.2 *In vivo* digestibility

The *in vivo* OM digestibility (OMD) of the WCCS investigated in Paper I and its relationship to stage of maturity is presented in Figure 7. The OMD followed the same pattern as IVOMD by decreasing between the heading and milk stages of maturity and then levelling off between the milk and dough stages for the barley crops but increasing for the wheat. The NDF digestibility and NDF concentration explained the majority of the variation in OMD, as seen by the negative linear relationship between undigested NDF (g kg^{-1} DM) and OMD (Figure 1, Paper I). According to Paper I, there was a positive linear relationship between IVOMD and OMD.

The OMD of the whole-crop barley silage (WCBS) investigated in Paper III was calculated from diet digestibility, assuming the OMD of soybean meal to be 900 g kg^{-1} OM, and was found to be 730 (g kg^{-1} OM) for the 'heading stage-long' treatment, 707 for 'heading stage-chopped', 643 for 'dough stage-long' and 656 for 'dough stage-chopped'. There was an effect of maturity (P<0.001, sed 18.6) but no effect of chopping and no interaction between maturity and chopping. The OMD of the chopped WCBS in Paper III is also included in Figure 7.

4.2.3 Calculated ME

According to calculations based on the IVOMD values presented in Figure 7, the mean ME (MJ kg^{-1} DM) of the WCCS was 8.9, with a range of 9.1-10.3 at the heading stage, 8.1-9.4 at the milk stage and 7.6-9.3 at the dough stage of maturity.

4.3 Intake

4.3.1 Intake in relation to maturity and silage characteristics

The averege DM intake in relation to maturity of the WCCS (g kg^{-1} LW) for the experiments in Papers I-IV is described in Figure 9. Intake was higher at the dough stage compared with the milk stage of WCBS maturity in Paper II, but variable responses to maturity of the different whole crops were found in Paper I and there was no difference between the heading stage and the dough stage of maturity in Paper III. However, intake of the chopped WCCS was never lower when harvested at the dough stage compared with the heading and milk stages of maturity.

The NDF intake declined with maturity in Papers II (see Table 3 in Paper II) and III (Table 2 in Paper III), while it varied for the different crops in Paper I (Table3 in Paper I).There were correlations between both DM (0.70) and NDF (-0.62) concentrations and DM intake in the overall comparison. The DM and NDF concentrations were negatively correlated (-0.46) and after adjusting for the effect of each on the other, there was a positive partial correlation between DM concentration and DM intake (g kg^{-1} LW) of WCCS (0.54) and a weaker negative partial correlation between NDF concentration and DM intake (g kg^{-1} LW) of WCCS (-0.35). There was a negative linear relationship between dietary NDF concentration and total DM intake (g kg^{-1} DM, Figure 10), which was unaffected by WCBS DM concentration. There was a negative correlation between DM intake and IVOMD (-0.46) but after adjusting for DM content there was no effect of IVOMD on DM intake (r = -0.01).

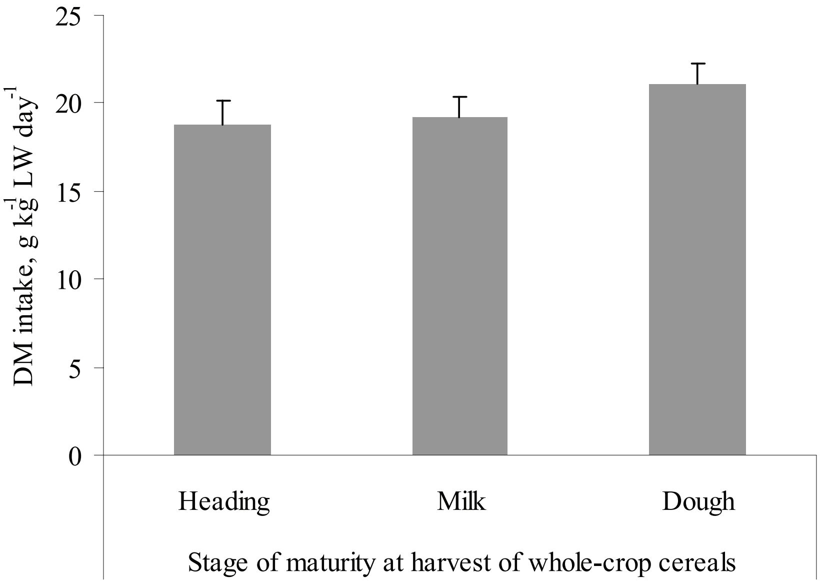

Figure 9. Dry matter (DM) intake per kg live weight (LW) and day of whole-crop cereal silage by heifers and steers receiving up to one kg of concentrate. Averages of experimental means and standard deviation of the averages (T-bars). Heading: n=6, Milk stage and Dough stage: n=9.

Of the fermentation products, the only correlations with DM intake (g kg^{-1} LW) of WCCS seemed to be for acetic acid (-0.70) and lactic acid (-0.60). However, acetic and lactic acid were positively correlated (0.78) and after adjusting for the effect of each acid on the other, there was a negative partial correlation between DM intake and acetic acid (-0.46) but no partial correlation between lactic acid and intake.

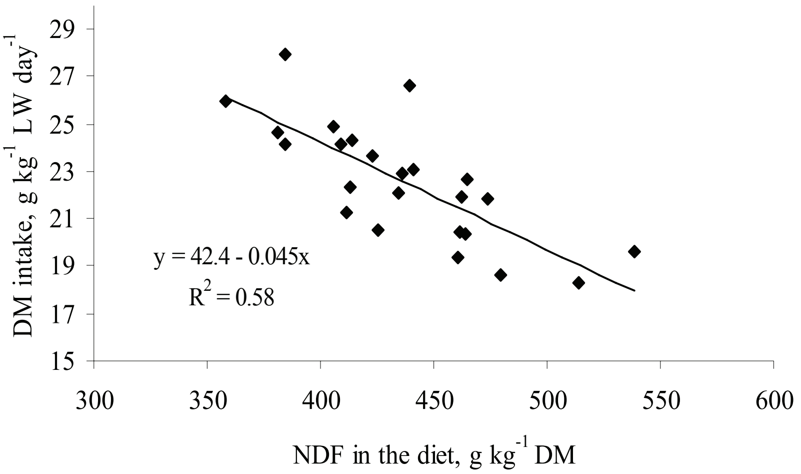

Figure 10. Relation between the dietary concentration of neutral detergent fibre (NDF) and dry matter (DM) intake by heifers and steers fed diets with whole-crop cereal silages and up to one kg of concentrate.

4.3.2 Intake in relation to physical form

Chopping increased intake at the dough stage of maturity for heavy steers (Table 2 in Paper III) and light steers (Table 2 in Paper IV) but not at the heading stage of maturity in Paper III. Chopping increased eating time and chewing activity during eating, but could not be related to the difference in intake between long and chopped WCBS harvested at the dough stage in Paper III. The greater intake due to chopping at the dough stage of maturity was related to diet selection in both Papers III and IV, but the selection pattern was different for light and heavy steers (Table 4). The heavy animals receiving chopped WCBS selected for starch, whereas the heavy steers receiving unchopped WCBS did not select. The light steers receiving chopped WCBS did not select in the diet but the light steers receiving unchopped WCBS selected for the non-starchy food components, or rather selected from the starchy food components.

Table 4. *Intake and diet selection of starch by light and heavy steers fed long or chopped whole-crop barley silage (WCBS) harvested at the dough stage of maturity (Papers III and IV).*

	Size of steers	
	Light	Heavy
Dry matter intake of WCBS, g kg^{-1} live weight		
Long	16.3	20.1
Chopped	19.8	21.2
Significance	***	**
Starch, g kg^{-1} dry matter, in		
Long WCBS	17.3	16.6
Orts	20.7	16.2
Significance	**	n.s.
Chopped WCBS	15.7	17.1
Orts	14.5	8.7
Significance	n.s.	***

** *P<0.01,* *** *P>0.001, n.s. = non significant*

4.4 LWG and feed conversion

In Paper II, live-weight gain was improved by 22% for the light steers and 31% for the heavy steers by feeding WCBS harvested at the dough stage of maturity compared with the milk stage. Feed intake was increased by 15% for the light steers and 17% for the heavy steers. Hence, feed utilisation was greater for the steers receiving the dough stage silage compared with the heading stage silage. Chopping the WCBS in Paper IV increased the LWG by 22% and the WCBS intake by 24%. Hence, the feed conversion ratio was not altered.

5 Discussion

5.1 Whole-crop cereal composition

The overall decreasing NDF concentration in the WCCS with maturation is in agreement with earlier findings (Khorasani *et al.*, 1997; Crovetto *et al.*, 1998; Micek *et al.*, 2001a). However, without grain losses at the milk and especially at the dough stage of maturity, the NDF concentration would have decreased even more. Based on the average grain loss per hectare and average harvested yield, grain losses were estimated to be 6% of the harvest. By assuming an NDF concentration in the grain of 220 g kg^{-1} DM and a starch concentration of 600 g kg^{-1} DM (Stacey *et al.*, 2006) at the dough stage, the NDF concentration would have decreased by 14 g kg^{-1} DM and the starch concentration would have increased by 25 g kg^{-1} DM if grain losses had been zero. These differences would be greater in crops harvested as bales than in precision-chopped crops due to the higher losses at baling.

The modest decrease in crude protein concentration with maturity is in agreement with general findings (Mannerkorpi & Taube, 1995; Khorasani *et al.*, 1997; Crovetto *et al.*, 1998; Micek *et al.*, 2001a). Lignin concentration increased with maturity, as also reported by Cherney *et al.* (1983) and Filya (2003). However, Mannerkorpi & Taube (1995), Khorasani *et al.* (1997) and Nadeau (2007) found no changes in lignin concentration due to maturity in WCC. The positive correlation between lignin and INDF was similar to correlations reported by Traxler *et al.* (1998) for grasses and legumes, but Huhtanen *et al.* (2006) reported an even stronger linear relationship in WCC.

5.2 Digestibility

The digestibility measured *in vivo* and *in vitro* followed the same pattern and declined between the heading and milk stages of maturity and then levelled off between the milk and dough stages. These results are in agreement with many previous findings (McCullough & Sisk, 1967; Cherney & Marten, 1982a; Helsel & Thomas, 1987; Südekum *et al.*, 1991a; Garnsworthy & Stokes, 1993; Crovetto *et al.*, 1998; Micek *et al.*, 2001b). The linear relationship between *in vivo* and *in vitro* digestibility suggests the *in vitro* method to be a promising tool for predicting *in vivo* digestibility in WCC. Wallsten (2008), in a parallel study to that reported in Paper I, found declining OMD between the heading and milk stages in oats grown in the north of Sweden. No difference in OMD was found between the milk and dough stages in the oats and or between the milk and dough stages of barley grown in the extreme south of Sweden, findings that are in agreement with Paper I. However, no effect of maturity was observed on OMD of six-rowed barley grown in northern Sweden (Wallsten, 2008).

The higher *in vivo* digestibility of the WCBS from Paper III in comparison with the crops from Paper I was probably due to the indirect estimation with AIA as an internal marker in the crops from Paper III. This is supported by the lower IVOMD values of the WCC from Paper III compared with those from Paper I. Furthermore, in an evaluation with the WCCS from Paper I, digestibility was overestimated by an average of 5% when calculated from AIA concentrations compared with total collection (Reza Daneshpajooh, unpublished data).

The variation in OMD was mainly explained by the concentration and digestibility of NDF, as indicated by the close relationship between undigested NDF and OMD in Paper I. Including undigested starch as an explanatory variable brought about a minor improvement in the relationship due to improving the degree of explanation at the dough stage of maturity. The linear relationship between undigested NDF and IVOMD and the similarity to the relationship between INDF and IVOMD suggest that the *in vivo* NDF digestibility was explained by intrinsic factors within the NDF fractions at all stages of maturity and that for example starch did not affect NDF digestibility negatively.

Despite the relatively high depression in starch digestibility in barley harvested in Uppsala in Paper I, the amount of starch passing out undigested was moderate, on average 22 g kg^{-1} DM ingested WCC, due to the relatively low starch concentration of the silage. However, there was a substantial variation in the starch concentration between the WCCS in the experiments. At the highest concentration starch losses would have been almost 1.5 the above estimate, assuming the same digestibility, and with reduced field losses of grain and, consequently, higher starch concentration of the crop, the faecal losses of starch would have been even higher. Precision chopping reduced the number of kernels in the faeces in Paper III, but as there was no difference in OMD between the long and chopped WCCS, the possible effect of chopping on grain digestion was not enough to change OMD. Mechanical processing of WCBS in specially equipped precision choppers has not proven successful either (Eun *et al.*, 2004). Hence, when fed to cattle, WCBS should probably be harvested no later than the soft dough stage.

5.3 Calculated ME

The calculated ME values (range 7.6-10.3 MJ kg^{-1} DM) were lower and the range narrower than those determined by Givens *et al.* (2009) *in vivo* in sheep (8.7-11.8 MJ kg^{-1} DM in whole-crop wheat and 7.9-11.2 MJ kg^{-1} DM in whole-crop barley). The average ME, 8.9 MJ kg^{-1} DM, was also lower than the value of 9.8 given in Swedish feed tables (Spörndly, 2003), which is calculated from the raw analysis (ash, CP, crude fat and crude fibre) and coefficients for digestibility and ME. The reason for the values being lower than those reported by Givens *et al.*(2009) might be the relatively low starch concentrations compared with those reported by Givens *et al.* (2009) (range 192-303 g kg^{-1} DM) and possibly by the fact that some crops in the report by Givens *et al.*(2009) were treated with urea, which can increase digestibility (Adesogan *et al.*, 1998). Garnsworthy & Stokes (1993) reported ME values between 8.5 and 10.0 MJ kg^{-1} DM in wheat, with starch concentration between 125 and 248 g kg^{-1} DM harvested on three cutting dates, while Crovetto *et al.* (1998) reported ME decreasing from 10.8 to 9.3 MJ kg^{-1} DM from the mid-bloom to dough stages, with a starch concentration of 188 kg^{-1} DM at the dough stage. Hence, our calculated ME values seem realistic, even though there are several possible sources of error in the calculations from IVOMD to ME. The most important uncertainty is probably the assumed difference in digestion between cattle and sheep. According to the equation, digestibility is equal for the two species at an OMD of 655 g kg^{-1}. At lower OMD values the digestibility is lower for sheep than for cattle, while at higher OMD values it is higher for sheep than for cattle. At the lowest IVOMD in the present studies, the calculated OMD for sheep was 43 g kg^{-1} lower than for cattle. These results are in accordance with Südekum *et al.* (1995), who found similar digestibility in sheep at maintenance feeding and steers at *ad libitum* feeding when fed whole-crop wheat at the late milk stage of maturity, with an OMD of 707 g kg^{-1} for the steers, but better digestibility in the sheep at later stages of maturity. However, with cattle and sheep fed whole-crop barley and wheat at maintenance, Kirchgessner *et al.* (1989) found higher digestibility in the sheep, with OMD values between 575 and 678 g kg^{-1}. These results from Kirchgessner *et al.* (1989) could be questioned, however, as they used total collection when estimating digestibility in the sheep and indirect measurement with chromium oxide as a marker for the steers. Aerts *et al.* (1984) compared different forages and found lower digestibility in sheep compared with cows when the quality declined. They also found similar digestibility of whole-crop barley silages with OMD of 600-610 g kg^{-1} in sheep and cows, when fed at maintenance level. However, any possible difference in digestibility between sheep and cattle seems to be relatively small. By assuming similar digestibility for sheep at maintenance as for the heifers at *ad libitum* intake in Paper I, the range in ME would be 8.2-10.1 MJ kg^{-1} DM and hence slightly narrower than the initial calculation. Despite the uncertainty in the calculations, it seems likely that the ME of the WCCS from these experiments is within the range given by Wilkins & Kirilov (2003) and modest in comparison with grass and maize silage. It also seems likely that WCC harvested at late stages of maturity are better suited for cattle than for sheep, as long as starch digestibility is not restricted.

5.4 Intake

When harvested at the dough stage of maturity intake of WCCS was greater than, or similar to, that of WCCS harvested at earlier stages. The main reason for this seems to be higher DM content at the dough stage. The decreasing NDF concentration with maturity also seemed to affect intake, which supports findings by Mertens (1994) and Steen *et al.* (1998). The different responses to maturity in terms of intake between the heading and milk stages in different silages might be caused by the effects of the DM and NDF concentrations, which were inconsistently related to maturity in some of the crops. The lack of impact of digestibility (IVOMD) on intake should be noted and is a characteristic that distinguishes WCC from grass silage (Steen *et al.*, 1998; Huhtanen *et al.*, 2007).

Although a good predictor of DM intake, the DM content itself is probably not the reason for low intake of silage. The reason is more likely to be the concentration of fermentation products, which is generally positively correlated to silage moisture content (Dulphy & VanOs, 1996). The negative relationship found between acetic acid and intake is in agreement with earlier findings, but according to Dulphy & Van Os (1996) acetic acid alone probably does not affect intake negatively but rather acts in combination with other factors related to fermentation quality. The silages in Papers I-IV were generally well fermented but had a relatively high concentration of NH_3-N. Ammonia nitrogen concentration is also thought to affect silage intake negatively, as high concentrations might reflect low fermentation quality. However, in WCCS NH_3-N in the fresh crop can be high (Nadeau, 2007) and hence high concentrations of ammonia might not be caused by fermentation in WCCS and thus might not have an impact on intake.

The positive effect of chopping on intake of WCBS harvested at the dough stage (Papers I and IV) was probably due to the absence of long awns, which seemed to restrict intake in unchopped silage. Awns did not seem to affect intake in WCBS harvested at the heading stage of maturity and these differences due to maturity are in accordance with results reported by Wallsten *et al.*(2009). There was no diet selection in the experiment in Paper I and no signs of negative effects of awns on intake. A contributing reason for this might have been that these crops were cut during baling and the bales were broken up in a mixer-wagon before feeding. The greater effect on intake among the light steers (Paper IV) indicates a higher sensitivity to awns in young animals compared with old. This is supported by the starch refusal of the light steers. Bolsen & Berger (1976) reported negative effects on intake of lambs when fed awned wheat compared with awnless but no effect in steers (234 kg), suggesting differences in sensitivity between the species. In the feeding trials with the light steers (Paper IV), minor infections in the mouth were observed occasionally with the chopped WCBS, but no such problems were observed with the older animals. This suggests that late harvested awned WCC (chopped or unchopped) is not well-suited for young ruminants.

The increased eating rate and consequently shortened eating time due to chopping did not affect intake in the study in Paper III. Contrary to this, positive relationships between intake and eating rate have been reported for mature steers (McLeod & Smith, 1989) and mature wethers (Antuna & Moseley, 1988). However, in a study where a number of factors potentially affecting feed intake were examined by a modelling approach, Poppi *et al.* (1994) concluded that rate of intake did not have a limiting effect on intake of stall-fed growing cattle. Poppi *et al.* (1994) suggested that intake rate might limit intake under poor grazing conditions, when eating time might approach the expected maximum of 12 hours a day. The results of Poppi *et* *al.* (1994) are supported by the eating time reported in Paper III and in other studies with stall-fed growing cattle, where eating time did not exceeded 9 hours (Deswysen & Vanbelle, 1978; Jaster & Murphy, 1983; Teller *et al.*, 1993; Luginbuhl *et al.*, 2000). Furthermore, the greater eating rate at restricted feeding in Paper III indicates that the animals had the potential to eat more efficiently if needed and hence decrease eating time if that became limiting to intake. Hence, it is doubtful whether eating rate has the potential to limit intake in stall-fed growing cattle when access to food is unrestricted, either directly or indirectly by limiting rumination time as suggested (Teller *et al.*, 1993; Van Soest, 1994). However, eating rate might be important in situations when animal access to food is restricted or when group-fed animals compete for limited amounts of feed (Forbes, 2007).

It is also questionable whether rumination time *per se* can limit intake in stall-fed growing cattle in practical situations. Welch (1982) showed that intake was undoubtedly depressed in cattle when rumination time was limited by experimental means. However, it is difficult to find a validated time limit for rumination of unrestrained cattle in the literature. Welch (1982) states that ruminating time is commonly 8-9 hours and claims the upper limit to be 10 hours, but does not present any proof for these figures. Wilson & Kennedy (1996) mention 10 to 12 hours as the maximum rumination time per day, but the origins of these figures are also somewhat obscure. The suggested maximum time for rumination is longer than that reported in Paper III (502-542 minutes day^{-1}). In other studies with growing cattle, rumination time varied between 460 and 580 minutes day^{-1} and did not reach the expected maximum time either (Deswysen & Vanbelle, 1978; Jaster & Murphy, 1983; Teller *et al.*, 1993; Luginbuhl *et al.*, 2000). If chewing time becomes an intake limiter for growing cattle, the quality of the forage must be low (Van Soest, 1994). Any effect of eating and chewing behaviour on intake in Paper IV can probably be excluded for reasons mentioned above. If chopping had limited intake due to effects on chewing behaviour it would have been through differences in rumination time, but according to Paper III rumination did not differ between long and chopped WCBS and hence probably did not have an influence on the difference in intake in Paper I.

The intake results were clearer in Papers II and IV than in Papers I and III, which was presumably mainly due to the feed and animal characteristics, as reported, in those experiments. However, the possibility cannot be excluded that the experimental design had an influence on the results. In the cross-over designs used in Papers I and III, intake was recorded over comparatively short periods (10 days), which is not uncommon in these kinds of experiments. However, it is questionable whether these relatively short time periods are relevant to practical situations, as day to day variation in feed intake is considerable. Burns *et al.* (1994) suggest an intake measurement period of 14 days after 7 days of adjustment, referring to measurement errors for sheep reported by Blaxter *et al.* (1961). However, according to Ingvartsen (1992), period length should be 3-5 weeks in a cross-over experiment (Latin square) with four animals if differences in DM intake of less than 6% are to be detected.

5.5 Live-weight gain

Live-weight gain increased with maturity and was caused by greater DM intake at the dough stage, as IVOMD did not differ between the milk and dough stages. The increasing LWG due to chopping in Paper IV was also due to greater intake. However, the lack of difference in feed conversion ratio between the long and chopped silage was surprising. As in Paper II, feed conversion ratio was expected to be lower in the steers with the greater LWG, especially as the animals fed the unchopped silage selected for the fibrous parts of the feed, which decreased the concentration of digestible nutrients.

5.6 When to harvest

As mentioned in the introduction, the decision on when to harvest WCC depends on several factors. If only crop production and animal production aspects are considered, the recommendation by Sotola (1937) to harvest at the dough stage of maturity is still valid. At the dough stage, the harvested yield is high, intake is high and digestibility is acceptable. This combination results in low feed costs and good animal performance. However, harvest of WCBS should not take place after the mid-dough stage, due to the risk of declining starch digestibility. The increased risk of grain losses at later stages of maturity should also be considered.

Digestibility, and hence energy concentration, can clearly be controlled by harvesting time, but if higher digestibility is the goal, harvesting should not take place later than the heading stage of maturity. At earlier stages of maturity, digestibility is even higher (Südekum *et al.*, 1991b) but crop yield is lower. If the crop is harvested earlier than the dough stage it should definitely be wilted in order to avoid depression of intake. However, due to decreasing NDF concentration, harvesting at the dough stage is probably associated with greater intake even if similar DM content can be achieved by wilting, as long as the grain losses are kept at a minimum.

Protein content decreased with maturation and that might be another reason for harvesting earlier than the dough stage. For older growing cattle the CP concentration of WCC might be enough to fulfil the animal requirements when the WCC is harvested at earlier stages of maturity, but this is not the case for young cattle.

When harvesting with machinery designed for grass crops, the risk of grain losses should also be considered, as should the fact that these increase with maturity.

5.7 How to harvest

Harvesting technique definitely has an impact on the feeding value of WCC. Harvesting whole crops as round bales is not the best option due to the risk of grain losses, which are greater than when crops are precision-chopped after mowing or, even better, when they are direct cut at chopping. However, the problems with storage stability are lower with round bales compared with bulk silos as round bales are generally consumed shortly after being exposed to the air, which might not be the case with silos. Grain losses during harvest can also be reduced by using a mower without conditioner and by choosing a suitable type of baler. Lingvall *et al.* (2005) compared losses in two types of round balers and concluded that a machine that produced bales with a soft core was more aggressive to the crop material during baling and hence caused greater losses than a baler that produced bales with a hard core, as was used in the experiments in Papers I, III and IV. A precision chopping harvester with a cutter bar is probably the best machine for harvesting WCC.

6 Conclusions

Whole-crop barley or wheat should be harvested either no later than the heading stage or at the dough stage of maturity to promote good performance of growing cattle. At the heading stage, digestibility is higher but crop yield is low and wilting is necessary to avoid depression of feed intake. At the dough stage of maturity, digestibility is lower but feed intake and crop yield are high. Wilting is not necessary at the dough stage, making the forage quality more predictable than at the heading stage. Harvesting should not take place later than the soft dough stage of maturity to avoid reductions in starch digestibility, especially in barley crops. Grain losses during harvesting can decrease crop yield, intake and digestibility. The risk of grain losses increases with stage of maturity and with harvesting machinery that works the crop heavily, *e.g.* mower conditioner and round baler), while harvesting should preferably take place at the early dough rather than the soft dough stage.

To avoid intake depression, whole-crop barley should preferably be chopped or reduced in size when harvested at the dough stage of maturity. This is especially important when fed to young cattle.

7 Future perspectives

Whole-crop cereals are comparably cheap to produce in Sweden and their lack of competitiveness in relation to grass and clover is mainly due to the EU subsidies available for grassland. Without such subsidies the production costs are fairly similar and if subsidies disappear in the future, the interest in whole crops might change. The nutritive value of whole-crop cereals is still less than can be achieved with grass and clover, and this is the main limitation when using WCC in animal production.

The feed value of WCC can be improved by several means. The most obvious is to use species and varieties with the highest nutritional value. Winter wheat and barley generally have the highest digestibility of the cereals and as oats is a common whole crop in Sweden, one way of improving the feed value would be to replace oats with barley. The use of winter wheat as a whole crop is limited and one option would be to increase the area on which it is grown. Wheat might also be better suited to young animals than barley due to the lack of awns. Awnless varieties of barley are used for whole-crop cereals in other countries (*e.g.* Australia) and ought to be tested in Sweden. Another possibility might be hull-less barley, which should have higher energy value compared with hulled barley due to its lower fibre concentration. Hull-less barley has lower starch digestibility than hulled, but this might not be a problem in whole-crop silage. Starch can be broken down during ensiling of whole-crop cereals and while being a potential draw-back with regular barley it might be an advantage in hull-less barley, possibly increasing starch and hence feed digestibility.

As fibre concentration has a determining influence on organic matter digestibility, a logical way to improve the feed value of WCC would be to reduce the proportion of straw and leaf in the whole-crop. This can be done by using short straw varieties or raising the cutter-bar when harvesting the crop. However, shorter straw varieties and higher stubble height generally only result in decreased crop yield and not in improved animal performance. This is an intriguing question that is poorly studied and should be explored by investigations of digestive physiology.

The nutritional characteristics of WCC could perhaps be improved by delayed sowing date. Delayed sowing date could also be used as a means of adjusting the date of harvest, which can fall between the first and second cuts of grass silage in some parts of Sweden. Delaying sowing could at best result in a cereal whole crop of better quality that is ready to harvest at the same time as the grass crop.

If time of harvest were to be synchronised, whole-crop cereals could also be co-ensiled with clover-grass crops. The advantages are several, especially with a clover-dominated crop. Clover is often difficult to wilt and combining it with a dry whole crop would increase the DM content without wilting, resulting in enhanced ensiling properties and reduced risk for effluents, which might have negative effects on the environment. Increased DM content would potentially increase DM intake and the increased fibre concentration originating from the whole crop has the potential for positive dietary effects, which might improve faecal consistency and thereby the animal environment.

Whole-crop cereals could also be used more as a tool for improving the utilisation of protein produced on-farm. By combining clover-grass silage and WCC in the diet of growing cattle, the need for protein supply would be reduced, as would any potential CP surplus from the grass silage. This is especially interesting in organic farming, where clover often makes up a large part of the ley.

Overall, the flexibility of WCC is probably its main advantage in both crop production and animal production. Therefore, WCC could be used more to optimise forage production. A deficit in the forage supply is costly in a farm enterprise but a surplus can also be expensive. To balance fluctuating grass production between years, a flexible proportion of the forage produced could be WCC, the amount of which could be adjusted to the situation in each year. In order to utilise this opportunity to the full, more attention needs to be focused on harvesting and storage of whole-crops at late stages of maturity, i.e. hard dough or later, as the forage supply situation might not be clear until fairly late in the growing season. The problems with decreased starch digestibility, mainly in barley, need more attention. The storage of these dry crops might also be a problem. The use of urea as a conserving agent is not uncontroversial due to the risk of environmental losses of N and any alternative should preferably promote storage stability as well as improving fibre digestibility.

8 Populärvetenskaplig sammanfattning

Helsädesensilage är ett grovfoder som vanligtvis ges till nötkreatur. Helädesensilage kan göras av samtliga spannmålsslag men korn och havre är vanligast i Sverige medan vete är vanligast utomlands. Helsäd är en liten fodergröda i Sverige och odlas på en areal som motsvarar ca 5% av den areal som används till gräs och klöver.

Helsäd består av hela spannmålsgrödan, ax och strå, och skördas innan spannmålskärnorna mognat. Det skördade materialet kan antingen hackas och läggas i en silo utan lufttillträde eller rullas ihop till balar som plastas in. Egenskaperna hos helsädesensilage påverkas i stor utsträckning av när spannmålen skördas. Vid skörd i ett tidigt utvecklingsstadium liknar helsäden en gräsgröda men efterhand som den mognar fylls spannmålskärnorna med stärkelse och fodret liknar alltmer en blandning av kärnor och halm.

Smältbarheten, d.v.s. hur stor andel av fodret som bryts ned i djuret, bestämmer hur mycket tillgänglig energi som finns i foder. Smältbarheten i grovfoder beror i hög utsträckning på hur mycket fiber som finns i fodret och på fiberns smältbarhet. Fibersmältbarheten sjunker vanligtvis i helsäd, liksom i andra grovfodergrödor, men till skillnad från t.ex. gräs så sjunker fiberinnehållet i helsäd efter axgång p.g.a. att kärnorna fylls med stärkelse. När helsäden skördas i ett sent mognadsstadium kan smältbarheten sjunka p.g.a. att djuren inta kan smälta kärnorna. Detta är speciellt viktigt för nötkreatur eftersom de inte tuggar kärnor speciellt bra, till skillnad från får. Mognadsstadiet kan också påverka djurens konsumtion av helsädesensilage. Helsäden blir torrare ju mer mogen den blir och det innebär oftast att ensilage konsumtionen ökar. Som tidigare nämndes sjunker fiberinnehållet i helsäd efterhand den mognar och det har också oftast en positiv inverkan på konsumtionen hos djur.

I Sverige skördas mycket helsäd som rundbalsensilage medan den utomlands oftast hackas och läggs i silo. Det finns nästan inga undersökningar gjorda där man studerat skillnaden mellan långt och hackat helsädesensilage. Från studier med andra grovfodermedel vet man att hackning kan öka djurens konsumtion, t.ex. p.g.a. att det går snabbare att äta eller att djuren behöver kortare tid att idissla foder, .

Syftet med den här avhandlingen var att studera hur mognadsstadium och hackning av helsäd påverkar smältbarheten, konsumtionen och tillväxten hos växande nötkreatur.

Konsumtion och smältbarhet studerades hos mjölkraskvigor som utfodrades med helsädesensilage av korn och vete som skördats vid axgång (precis när axet kommit fram ur översta bladet), mjölkmognad (när kärnorna är fyllda med vattnigt innehåll) och degmognad (när kärnorna fylls med stärkelse och är halv-hårda när man klämmer på dem). Större och mindre mjölkrasstutar (kastrerade tjurar) utfodrades med helsädesensilage av korn varvid konsumtion och tillväxt studerades. Foderkonsumtion och ätbeteende studerades hos större mjölkrasstutar som utfodrades med långt och hackat helsädesensilage som skördats vid axgång och degmognad. Foderkonsumtion foderselektion och tillväxt studerades hos unga mjölkrasstutar som utfodrades med långt eller hackat helsädesensilage skördat vid degmognad.

Resultaten visade att smältbarheten sjunker mellan axgång och mjölkmognad men förblir i stort sett oförändrad mellan mjölk- och degmognad. Överlag åt djuren mer när helsäden skördades vid degmognad jämfört med mjölkmognad och axgång. Det berodde på att ensilaget oftast var torrare vid degmognad och att fiberinnehållet var lägre. På grund av att de åt mer växte de djur som fick helsädesensilage skördat vid degmognad bättre än de som fick det som skördats vid mjölkmognad. Foderkonsumtionen ökade när helsäd som skördats vid degmognad hackades men hackning påverkade inte konsumtionen av det som skördats vid axgång. Djuren åt snabbare av det hackade fodret men idisslingstiden påverkades inte. Ät och tuggningsmönstret hade inget inflytande på foderkonsumtionen. Den lägre konsumtionen av det långa helsädesensilaget skördat vid degmognad tycktes bero på att djuren ogillade de borst som finns på kornkärnor. De yngre stutarna tycktes känsligare för borsten än de äldre och sorterade i viss utsträckning bort kärnor och borts när de åt. Det skilde mer i konsumtion mellan långt och hackat ensilage hos de yngre djuren jämfört med de äldre. De yngre djuren som fick hackat ensilage växte betydligt bättre an de som fick långt p.g.a. att de åt mer.

Sammanfattningsvis skall helsäd skördas antingen vid axgång när smältbarheten är högre eller vid degmognad när konsumtionen är högre. Om den skördas vid degmognad skall helsäden helst hackas åtminstone om den skall utfodras till yngre nötkreatur.

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