Invited Review: Production and Digestion of Supplemented Dairy Cows on Pasture

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ABSTRACT

Literature with data from dairy cows on pasture was reviewed to evaluate the effects of supplementation on intake, milk production and composition, and ruminal and postruminal digestion. Low dry matter intake (DMI) of pasture has been identified as a major factor limiting milk production by high producing dairy cows. Pasture DMI in grazing cows is a function of grazing time, biting rate, and bite mass. Concentrate supplementation did not affect biting rate (58 bites/min) or bite mass (0.47 g of DM/bite) but reduced grazing time 12 min/d per kilogram of concentrate compared with unsupplemented cows (574 min/d). Substitution rate, or the reduction in pasture DMI per kilogram of concentrate, is a factor which may explain the variation in milk response to supplementation. A negative relationship exists between substitution rate and milk response; the lower the substitution rate the higher the milk response to supplements. Milk production increases linearly as the amount of concentrate increases from 1.2 to 10 kg DM/d, with an overall milk response of 1 kg milk/kg concentrate. Compared with pasture-only diets, increasing the amount of concentrate supplementation up to 10 kg DM/d increased total DMI 24%, milk production 22%, and milk protein percentage 4%, but reduced milk fat percentage 6%. Compared with dry ground corn, supplementation with nonforage fiber sources or processed corn did not affect total DMI, milk production, or milk composition. Replacing ruminal degradable protein sources with ruminal undegradable protein sources in concentrates did not consistently affect milk production or composition. Forage supplementation did not affect production when substitution rate was high. Fat supplementation increased milk production by 6%, without affecting milk fat and protein content. Increasing concentrate from 1.1 to 10 kg DM/d

reduced ruminal pH 0.08 and $\text{NH}_3\text{-N}$ concentration 6.59 mg/dl, compared with pasture-only diets. Replacing dry corn by high moisture corn, steam-flaked or steam-rolled corn, barley, or fiber-based concentrates reduced ruminal $\text{NH}_3\text{-N}$ concentration 4.36 mg/dl. Supplementation did not affect in situ pasture digestion, except for a reduction in rate of degradation when high amounts of concentrate were supplemented. Supplementation with energy concentrates reduced digestibility of neutral detergent fiber and intake of N but did not affect digestibility of organic matter or flow of microbial N.

(**Key words:** high producing dairy cow, pasture, supplementation, milk production and composition)

Abbreviation key: CDMI = concentrate DMI, CBW = change in BW, ED = effective degradability, FPr = fat percentage reduction, FYi = fat yield increase, HM = herbage mass, LEG = percentage of legumes in pasture, MN = microbial nitrogen, MPi = milk production increase, MR = milk response, MY = milk yield, NANMN = nonammonia, nonmicrobial nitrogen, NDFp = NDF in pasture available, NDFs = NDF in pasture selected, PA = pasture allowance, PASUP = pasture allowance and total supplementation interaction, PD = potentially degradable fraction, PDMI = pasture DMI, PDMir = pasture DMI reduction, PPi = protein percentage increase, PYi = protein yield increase, RAD = ruminal apparent digestibility as proportion of intake, RADD = ruminal apparent digestibility as proportion of total tract apparent digestibility, RUPi = RUP intake, SHT = sward height, SR = substitution rate, SUP = total supplementation, TB = number of bites per d, TDMI = total DMI, TDMi = total DMI increase, TOMi = total OM intake, TTAD = total tract apparent digestibility, WOL = week of lactation.

INTRODUCTION

The use of pasture for dairy cows results in lower-cost feeding systems because grazed forage is the cheapest source of nutrients (Clark and Kanneganti, 1998; Peyraud and Delaby, 2001). Efficient pasture-based systems are characterized by high milk output per unit of land, while confinement systems are characterized by high

Received April 5, 2002.

Accepted July 3, 2002.

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milk output per cow (Clark and Kanneganti, 1998). Pastures used for dairy cows are commonly based on temperate species, and are described as high quality or young and leafy pastures with 18 to 24% DM, 18 to 25% CP, 40 to 50% NDF, and 1.53 to 1.67 Mcal/kg DM of NE_L (Clark and Kanneganti, 1998). Muller and Fales (1998) reported a range of 18 to 25% CP, 40 to 55% NDF, and 1.55 to 1.70 Mcal/kg DM of NE_L for well-managed grass pastures typically grazed in the Northeastern United States.

In the United States, the dairy industry over the last 50 yr has been characterized by a favorable milk price:feed cost ratio; therefore, dairy systems have tended to focus on high milk production per cow (Clark and Kanneganti, 1998; Muller and Fales, 1998) and less use of pasture-based systems until recent years (Muller and Fales, 1998). Average milk production per cow in the United States increased from 3191 kg in 1960 to 8263 kg in 2000 (NRC, 2001). Besides the high milk production per cow, climatic conditions (i.e., cold temperatures and snow cover during 4 or 5 mo/yr) in many important dairy areas in the United States (e.g., Midwest and Northeast) do not permit year-round grazing systems (Clark and Kanneganti, 1998). Therefore, the use of feeding systems combining pasture plus additional feed supplements such as concentrates and conserved forage are required.

The main objective of supplementation of grazing dairy cows is to increase total DMI and energy intake relative to that achieved with pasture-only diets (Peyraud and Delaby, 2001; Stockdale, 2000b). For the production system, a primary goal of supplementation is to optimize profit per cow and per unit of land (Kellaway and Porta, 1993; Fales et al., 1995). The objectives of supplementation include (Kellaway and Porta, 1993): 1) increase milk production per cow, 2) increase stocking rate and milk production per unit of land, 3) improve the use of pasture with the higher stocking rate, 4) maintain or improve BCS to improve reproduction during pasture shortage, 5) increase length of lactation during periods of pasture shortage, and 6) increase milk protein content by energy supplementation.

Previous reviews of grazing research have focused on animal production and digestion aspects (Leaver, 1985; Kellaway and Porta, 1993; Doyle et al., 1996; Stockdale, 2000b). However, most of these reviews have focused on research with relatively low producing dairy cows. Appropriate strategies for supplementation of high producing dairy cows requires an understanding of the effect of different types of supplements on DMI, animal performance, and digestion, and of providing nutrients that complement the nutrient content of pasture and meet the nutrient requirements of dairy cows.

The objective of this review is to summarize the effect of supplementation on grazing behavior, pasture and total DMI, milk production, milk composition, and ruminal and postruminal digestion of high producing dairy cows on pasture. For the purpose of this review, high producing dairy cows are defined as those producing more than 25 kg/d of milk in early lactation or about 20 kg/d in late lactation. However, research data from low producing dairy cows are included in those areas where information with high producing dairy cows is not available. This review focused on research data from the United States, but because of limited published research in many areas, information was included from other countries where grazing systems are important (e.g., Argentina, Australia, France, Ireland, Netherlands, New Zealand, and United Kingdom).

DRY MATTER INTAKE OF GRAZING COWS

Dry Matter Intake of Grazing Cows on Pasture-Only Diets

Different theories about the control of DMI in ruminants have been presented (Forbes, 1995); however, detailed description of these theories exceeds the objectives of this review. Hodgson and Brookes (1999) described three factors affecting pasture DMI of grazing cows: 1) "feeding drive" or nutrient requirements of the cow; 2) "physical satiety" or factors associated with distension of the alimentary tract; and 3) "behavioral constraints" or limits to the potential pasture DMI resulting from the combination of pasture and animal factors affecting grazing behavior.

Low pasture DMI has been identified as a major factor limiting milk production of high producing cows with a grazing system (Leaver, 1985; McGilloway and Mayne, 1996; Kolver and Muller, 1998). Leaver (1985) suggested that high producing dairy cows fed pasture-only diets could reach a total DMI of 3.25% of BW. Mayne and Wright (1988) estimated that with no pasture quantity and quality restrictions, pasture DMI of high yielding dairy cows might reach 3.5% of BW. Beever and Thorp (1997) proposed that total DMI of high producing cows fed pasture-only diets is lower than for cows fed pasture diets plus concentrates. This may be explained by physical constraints, rate of forage removal from the rumen, and water consumption associated with pasture.

Studies in the United States with high producing cows fed pasture-only diets are limited (Kolver and Muller, 1998; Reis and Combs, 2000b; Bargo et al., 2002a). Kolver and Muller (1998) reported that early-lactation cows grazing high quality grass pasture in the spring had a pasture DMI of 19.0 kg/d, or 3.4% of BW. However, when compared with cows fed a nutri-

tionally balanced TMR ration, grazing cows consumed 4.4 kg less DM. The intakes of DM and NE_L were lower on the pasture-only diet; however, intakes of CP and NDF did not differ between the pasture-only diet and TMR. The difference in DMI, rather than energy content of pasture, appeared to be the major factor responsible for the lower total energy intake and milk production (Kolver and Muller, 1998). Pasture DMI of unsupplemented dairy cows increased from 17.7 kg/d or 2.9% of BW to 20.5 kg/d or 3.4% of BW as pasture allowance (PA) increased from 25 to 40 kg DM/cow per day (Bargo et al., 2002a). Although Dalley et al. (2001) suggested that pasture DMI may be increased by more frequent allocation of new pasture, they reported no difference in DMI (15.8 kg/d) or milk production (25.3 kg/d) of early lactation cows grazing a ryegrass pasture when offered one or six times per day.

Effect of Pasture Allowance

Many pasture factors affect DMI (Poppi et al., 1987; Hodgson and Brookes, 1999) including pregrazing pasture mass (amount of pasture per unit area; kg DM/ha) and PA (amount of pasture offered per cow; kg DM/cow per day). Several researchers (Stockdale, 1985; Dalley et al., 1999) have reported that pasture DMI is closely related to PA. The relationships between pasture DMI and PA have been described as asymptotic (Poppi et al., 1987; Peyraud et al., 1996; Dalley et al., 1999). However, it is unclear what PA is required to maximize DMI. In a review, Leaver (1985) proposed a maximum DMI at a PA between 45 to 55 g DM/kg of BW or 27 to 33 kg DM/cow per day for a 600-kg cow. Pasture DMI increased as PA increased, but at a declining rate with a plateau when PA was 10 to 12% of BW or 60 to 72 kg DM/cow per day for a 600-kg BW cow (Hodgson and Brookes, 1999). Data from Australia (Doyle et al., 1996) showed that pasture DMI continues to increase as PA increases up to 15 kg DM/100 kg of BW or 90 kg DM/cow per day for a 600-kg BW dairy cow. Pasture DMI increased curvilinearly from 11.2 to 18.5 kg DM/cow per day as PA increased from 20 to 70 kg DM/cow per day, with a plateau at a PA of 55.2 kg DM/cow per day (Dalley et al., 1999). Peyraud et al. (1996) reported a curvilinear relationship between pasture DMI and PA from 20 to 40 kg DM/cow per day, with pasture DMI reaching a plateau at a PA of 32.6 kg DM/cow per day. Wales et al. (1999) reported that as PA increased from 20 to 70 kg DM/cow per day, pasture DMI increased linearly from 7.1 to 16.2 kg DM/cow per day with a pregrazing pasture mass of 3100 kg DM/ha, and from 9.9 to 19.3 kg DM/cow per day with a pregrazing pasture mass of 4900 kg DM/ha.

Recent research has studied the effect of PA on pasture DMI of high producing dairy cows with no supplementation. Pasture DMI of dairy cows grazing an orchardgrass pasture was 17.5 and 20.6 kg DM/cow per day at low (25 kg DM/cow per day) and high (40 kg DM/cow per day) PA, respectively (Bargo et al., 2002a). In two experiments that measured PA at a 5-cm cutting height (Delaby et al., 2001), pasture DMI increased from 11.3 to 13.0 kg/cow per day as PA increased from 12.1 to 15.8 kg of DM/cow per day, and from 12.9 to 15.0 kg/cow per day as PA increased from 16.5 to 21.0 kg DM/cow per day. Stockdale (2000a) reported an increase in pasture DMI from 14.3 to 19.3 kg/d when PA of a ryegrass pasture was increased from 26.7 to 53.5 kg DM/cow per day. Dalley et al. (2001) also reported an increase of pasture DMI from 13.6 to 17.9 kg/d as the PA of a ryegrass pasture increased from 40 to 65 kg DM/cow per day. Pasture DMI by high producing dairy cows in early lactation increased from 11.2 to 15.6 kg/d when PA of a ryegrass pasture was increased from 19 to 37 kg DM/cow per day (Wales et al., 2001).

In summary, over a range of PA from 20 to 70 kg DM/cow per day, pasture DMI increased 0.19 kg/kg of increased PA (range: 0.17 to 0.24 kg/kg). Data from seven studies (Peyraud et al., 1996; Dalley et al., 1999; 2001; Stockdale, 2000a; Delaby et al., 2001; Wales et al., 2001; Bargo et al., 2002a) were used to describe the relationship between pasture DMI and PA for dairy cows on pasture-only diets. In those studies, cows ranged from 19 to 182 DIM and produced from 23.0 to 45.8 kg/d of milk at the start of the experiment, grazed at a PA from 12.1 to 70 kg DM/cow per day, and consumed 6.7 to 20.5 kg DM/cow per day of pasture. Observations were weighted as described by St-Pierre (2001) to account for unequal replications and variances of the means across studies. Pasture allowance and its quadratic term were considered as independent variables. Parameter estimates for the final equation were obtained using a mixed model approach (i.e., trial was considered a random effect) using the MIXED procedure of SAS (1999). The regression analysis for pasture DMI (PDMI, kg/d) resulted in a best-fit model that included terms for PA (kg DM/cow per day) and its quadratic term: $PDMI = 7.79 (SE 1.49) + 0.26 (SE 0.06) PA - 0.0012 (SE 0.0007) PA^2$; $R^2 = 0.95$. Based on this equation, the optimum PA to maximize pasture DMI (21.9 kg/d) is reached at 110 kg DM/cow per day, and pasture DMI increased 0.26 kg/kg of increase in PA up to 110 kg DM/cow per day.

If the goal is to maximize pasture DMI of high producing dairy cows, management must ensure unrestricted pasture quality and quantity, which is only found for short periods of time during the spring. Unrestricted pasture conditions (i.e., high PA) also implies low pas-

ture utilization (pasture DMI/PA < 50%; McGiloway and Mayne, 1996). The use of very high PA might also result in deterioration of pasture quality as the season progresses because of the increase in residual pasture height (Peyraud and Delaby, 2001). The studies reviewed indicate that maximum pasture DMI is achieved when PA is between 3 to 5 times the DMI, which is in agreement with the regression described above. However, even under unrestrictive pasture conditions, total DMI amounts achieved by high producing dairy cows are lower than those by cows consuming TMR (Kolver and Muller, 1998) or pasture plus supplements (Bargo et al., 2002a, 2002b). Because of low pasture utilization and deterioration of pasture quality at high PA, a practical recommendation is to provide a PA of 2 times the expected pasture DMI or 25 kg DM/cow per day of PA when cows are also fed supplements (Bargo et al., 2002a).

Methods and Equations to Estimate DMI in Grazing Cows

Estimation of DMI in grazing cows is more difficult and less accurate when compared with the determination of DMI by cows on confinement systems. An extensive review of the different methods and techniques to estimate DMI in grazing cows was published by Leaver (1982). Techniques may be classified as either pasture- or animal-based (Meijs et al., 1982). An extensive review of pasture measurement techniques can be found in Marnette (2000). The main disadvantage of pasture-based techniques is that pasture DMI is estimated as a group and not individually. The most common animal-based technique used is based on the estimation of fecal production and diet digestibility (Le Du and Penning, 1982; Peyraud, 1998): $\text{DMI} = \text{fecal production} / (1 - \text{digestibility of the diet})$. Fecal production is estimated using markers such as chromium oxide (Peyraud, 1998) and alkanes (Dove and Mayes, 1991; Dove and Mayes, 1996). A comparison between those two methods has been reported by Mallozzini et al. (1996), who concluded that estimation of pasture DMI was similar if a 95.5% recovery is assumed for chromium oxide.

Because estimation of DMI by grazing cows demands the use of labor-intensive and indirect techniques that have several sources of error, equations based on animal and pasture characteristics have been developed to predict DMI of grazing cows (Caird and Holmes, 1986; Vazquez and Smith, 2000). Caird and Holmes (1986) used data from nine experiments conducted with cows grazing ryegrass, consuming 1.2 kg/d of concentrate, and producing 21.5 kg/d of milk on average to predict total DMI. Animal variables included total OM intake (**TOMI**, kg/d), herbage OM intake, concentrate

DMI (**CDMI**, kg/d), BW (kg), milk yield (**MY**, kg/d), herbage OM digestibility, and week of lactation. Pasture variables included herbage mass (**HM**, tonne of OM/ha), PA (kg OM/cow per day), and sward height (**SHT**, cm). For rotationally grazed cows the best equation ($R^2 = 0.68$) was: $\text{TOMI} = 0.323 + 0.177\text{MY} + 0.010\text{BW} + 1.636\text{CDMI} - 1.008\text{HM} + 0.540\text{PA} - 0.006\text{PA}^2 - 0.048\text{PA} \times \text{CMDI}$.

Vazquez and Smith (2000) used data from 27 grazing studies with dairy cows to obtain regression equations to predict total and pasture DMI. Mean milk production and supplementation amount were 15.9 and 1.9 kg/d, respectively. Independent variables included 4% FCM (kg/d), days since calving, PA (kg DM), NDF in pasture available (**NDFp**, % DM), NDF in pasture selected (**NDFs**, % DM), percentage of legumes in pasture (**LEG**, %), amount of concentrate supplemented (kg DM), amount of forage supplemented (kg DM), total supplementation (**SUP**, kg DM), PA and total supplementation interaction (**PASUP**), BW (kg), and change in BW (**CBW**, kg/d). The best equation ($R^2 = 0.95$) for total DMI (**TDMI**) estimation was: $\text{TDMI} = 4.47 + 0.14\text{FCM} + 0.024\text{BW} + 2.00\text{CBW} + 0.04\text{PA} + 0.022\text{PASUP} + 0.10\text{SUP} - 0.13\text{NDFp} - 0.037\text{LEG}$. The best equation to estimate PDMI ($R^2 = 0.91$) was: $\text{PDMI} = 4.47 + 0.14\text{FCM} + 0.024\text{BW} + 2.00\text{CBW} + 0.04\text{PA} + 0.022\text{PASUP} - 0.90\text{SUP} - 0.13\text{NDFp} - 0.037\text{LEG}$.

Equations developed by Caird and Holmes (1986) and Vazquez and Smith (2000) differ from the equation presented by NRC (2001) to estimate DMI. While those equations included pasture and supplement variables, the NRC (2001) equation is based only on animal variables such as FCM (kg/d), BW (kg), and week of lactation (**WOL**): $\text{DMI} = (0.372 \times \text{FCM} + 0.0968 \times \text{BW}^{0.75}) \times (1 - e^{(-0.192 \times (\text{WOL} + 3.67))})$. We used a dataset of 56 measures from Bargo et al. (2002b), who measured DMI four times during the grazing season using Cr_2O_3 as a fecal marker in dairy cows that grazed an orchardgrass pasture and were supplemented with 8.7 kg/d of a corn-based concentrate. Cows, pasture, and supplement information reported in that study (Bargo et al., 2002b) were used to estimate DMI with the equations of Caird and Holmes (1986), Vazquez and Smith (2000), and NRC (2001). Total DMI estimated by the equations of NRC (2001) (21.9 kg/d) or Caird and Holmes (1986) (21.2 kg/d) did not differ from DMI measured by Cr_2O_3 (21.6 kg/d) ($P > 0.05$), but estimation of DMI by the equation of Vazquez and Smith (2000) (24.4 kg/d) was higher than measured DMI ($P < 0.05$). This indicates that estimation of DMI using the equations of Caird and Holmes (1986) and NRC (2001) was accurate for this particular dataset with high producing dairy cows, with the advantage that the NRC (2001) equation is simpler and requires only animal factors.

GRAZING BEHAVIOR

Methodology

Pasture DMI of grazing cows can be expressed as the product of grazing time (min/d), biting rate (bites/min), and bite mass (g DM/bite; Hodgson and Brookes, 1999; Rook, 2000). Few grazing behavior studies have been conducted with high producing dairy cows under practical or production conditions, probably because of methodological limitations. Bite mass can be measured directly by using esophageally fistulated animals or indirectly dividing pasture DMI by the total bites/d (Forbes, 1988; Rook, 2000). Because use of esophageally fistulated animals is expensive, and may compromise animal welfare and normal behavior, bite mass is often calculated indirectly (Rook, 2000). Both biting rate and grazing time can be measured visually or automatically (Forbes, 1988). Visual estimation of biting rate requires the recording of head movements and sound associated with pasture prehension. Automatic methods for biting rate are based on recording jaw and sometimes head movements. Visual grazing time measurements are based on recording grazing activity at different intervals (e.g., 5 to 10 min) with the disadvantages of being labor intensive and limited by daylight (Rook, 2000). Traditionally, automatic grazing time measurements are conducted using vibracorders (Forbes, 1988). Recently, an automatic method for grazing behavior estimation was developed (Rutter et al., 1997), which has several advantages such as fewer people required, less operator-associated errors, and more detailed behavior information (Champion et al., 1998).

Grazing Behavior on Pasture-Only Diets

Among the three grazing behavior variables, bite mass has the greatest influence on pasture DMI (Forbes, 1988; McGilloway and Mayne, 1996). Although bite mass is also affected by the animal's anatomy characteristics (e.g., mouth; Rook, 2000), it is principally determined by pasture-related characteristics (Hodgson and Brookes, 1999), such as pasture height (Phillips, 1993; McGilloway et al., 1999) and density (Rook, 2000). Pasture height is the major constraint on bite mass in temperate pastures, with the effect primarily on bite depth rather than on bite area (Rook, 2000). Dairy cows consistently remove around one-third of the height of pasture, regardless of pasture height (Wade et al., 1989). Bite mass decreases with a reduction in pasture height both in unsupplemented (Gibb et al., 1997; McGilloway et al., 1999) and supplemented (Rook et al., 1994) dairy cows.

In many grazing behavior studies, pasture height is expressed as sward surface height, which refers to the

height of the top surface of the leaf canopy on an undisturbed sward (Hodgson and Brookes, 1999). Gibb et al. (1997) reported that for dairy cows continuously grazing ryegrass, bite mass decreased from 0.31 g OM/bite at 7 or 9 cm to 0.23 g OM/bite at 5 cm, whereas neither biting rate (76 bites/min) nor grazing time (604 min/d) were affected by sward surface height. McGilloway et al. (1999) found that bite mass decreased from 1.28 to 0.85 g DM/bite in one experiment with reductions in sward surface height (from 21 to 7 cm) and from 1 to 0.66 g DM/bite in a second experiment with reductions in sward surface height (from 11 to 6 cm), while biting rate was not affected (56 bites/min in experiment 1; 62 bites/min in experiment 2). In a third experiment, an interaction was found between sward surface height and density; bite mass was reduced with reductions in sward surface height more at low pasture density (from 1.02 to 0.47 g DM/bite) than at high pasture density (from 0.97 to 0.63 g DM/bite; McGilloway et al., 1999).

Grazing time and biting rate are influenced by animal-related characteristics such as genetic merit and milk production. Both grazing time and biting rate act as compensatory mechanisms to avoid reductions in pasture DMI when bite mass decreases. However, these compensatory mechanisms have a limit. The upper limit of grazing time to compensate for a reduction in bite mass is determined for the time required for other activities such as ruminating (Rook, 2000). Under poor pasture conditions (e.g., very short pasture), all three variables decline (Hodgson and Brookes, 1999). High genetic cows had higher grazing time and biting rate than low genetic cows supplemented with concentrate (Bao et al., 1992). High genetic cows grazed a ryegrass pasture for longer time (218 vs. 204 min, measured visually for a period of 7 h) and at a higher biting rate (64 vs. 61 bites/min) than low genetic cows. Two recent studies (Pulido and Leaver, 2001; Bargo et al., 2002b) reported that high producing cows had greater grazing time, number of bites per day, and rate of intake than low producing cows. Bargo et al. (2002b) found a positive relationship between MY (kg/d) and the number of bites per day (**TB**, bites/d) for cows producing more than 25 kg/d of milk grazing a orchardgrass pasture and supplemented with 8.7 kg/d of concentrate: $MY = 14.1 + 0.0005 TB$ ($R^2 = 0.74$), which indicates an increase of 5 kg/d of milk for every 10,000 bites/d (Bargo et al., 2002b).

Effect of Supplementation on Grazing Behavior

Studies evaluating the effect of supplementation on grazing behavior of dairy cows are presented in Table 1. Increasing the amount of concentrate reduced grazing time but did not affect biting rate (Arriaga-Jordan and

Table 1. Effect of concentrate supplementation on grazing time (GT), biting rate (BR), and bite mass (BM) of dairy cows.

Reference	Cows ¹		Pasture ²	Supplement		GT min/d	BR bites/min	Total bites/d	BM g DM/bite
	DIM	Milk		Type ³	DMI, kg/d				
Arriaga-Jordan and Holmes, 1986	72	37.8	RG (rotational) ⁴	Barley	1	467 ^a	64 ^a	30,000	0.53 g OM/bite
					6	424 ^b	62 ^a	26,100	0.58
			RG (continuous) ⁴	Barley	1	525 ^a	75 ^b	39,400	0.47
					6	471 ^b	75 ^b	35,100	0.48
Bargo et al., 2002a	101	45.8	OG	Corn	0.8	609 ^a	56	34,419 ^a	0.55
					8.6	534 ^b	54	28,501 ^b	0.55
					0.7	626 ^a	56	35,235 ^a	0.60
					8.7	522 ^b	55	28,563 ^b	0.59
Delagarde et al., 1997	156	25.0	RG (0 kg N/ha) ⁵	Control	0.0	510	54	27,300	0.47 ^a g OM/bite
				Soybean meal	2.0	519	56	29,100	0.48 ^a
			RG (60 kg N/ha) ⁵	Control	0.0	546	54	29,000	0.53 ^b
				Soybean meal	2.0	517	54	27,900	0.54 ^b
Gibb et al., 2002	52	30.1	RG	Barley	0.0	591	57	32,967	0.32 g OM/bite
					1.2	610	60	35,800	0.33
					2.4	605	60	35,067	0.31
					3.6	610	59	32,333	0.33
					4.8	588	61	34,933	0.24
					6.0	572	61	33,400	0.29
Kibon and Holmes, 1987	75	32.4	RG (5 cm) ⁶	Control	0	596 ^a	78	47,000 ^a	0.32 ^a
				Cereal	3	571 ^b	77	44,000 ^b	0.36 ^a
				Beet-pulp	3	559 ^b	77	43,000 ^b	0.35 ^a
			RG (6.5 cm) ⁶	Control	0	585	76	45,000 ^a	0.39 ^b
				Cereal	3	550	76	42,000 ^b	0.39 ^b
				Beet-pulp	3	560	76	43,000 ^b	0.40 ^b
Rook et al., 1994	48	NA ⁷	RG/WC (4 cm) ⁶	Control	0	765 ^a	62	NA	0.28
				Gluten corn/beet pulp	4	553 ^b	45	NA	0.51
			RG/WC (6 cm) ⁶	Control	0	651	47	NA	0.52
				Gluten corn/beet pulp	4	660	61	NA	0.33
			RG/WC (8 cm) ⁶	Control	0	639 ^a	53	NA	0.54
				Gluten corn/beet pulp	4	606 ^b	52	NA	0.58
Sayers, 1999	207	NA	RG	Control	0.0	512 ^a	51	25,814	0.39
				Soybean meal (10) ⁸	2.6	537 ^a	46	24,724	0.44
				Soybean meal (18)	2.6	476 ^a	47	21,862	0.42
				Soybean meal (26)	2.6	507 ^a	50	25,092	0.43
				Soybean meal (34)	2.6	528 ^a	48	24,998	0.42
				Soybean meal (10)	5.2	491 ^b	47	22,997	0.40
				Soybean meal (18)	5.2	477 ^b	45	22,231	0.43
				Soybean meal (26)	5.2	453 ^b	45	20,826	0.44
				Soybean meal (34)	5.2	469 ^b	47	22,082	0.48
Sayers, 1999	40	NA	RG	Barley/wheat/corn	5	458 ^b	NA	21,302 ^b	0.61
				Barley/wheat/corn	10	358 ^d	NA	16,041 ^d	0.58
				Beet pulp/citrus pulp	5	480 ^a	NA	22,744 ^a	0.60
				Beet pulp/citrus pulp	10	398 ^c	NA	17,825 ^c	0.61

^{a,b,c,d}Means within reference with different superscript differ ($P < 0.05$).

¹Pre-experimental DIM and milk (kg/d).

²RG = perennial ryegrass (*Lolium perenne*); OG = orchardgrass (*Dactylis glomerata*); WC = white clover (*Trifolium repens*).

³Main source of energy or protein in the supplement.

⁴Grazing system.

⁵Fertilization amount.

⁶Pasture height.

⁷NA = Not available.

⁸%CP of the supplement.

Holmes, 1986; Kibon and Holmes, 1987; Rook et al., 1994; Bargo et al., 2002a; Gibb et al. 2002). Arriaga-Jordan and Holmes (1986) reported that grazing time was reduced 11 min/kg of concentrate in continuous grazing and 8 min/kg of concentrate in rotational grazing, while biting rate was not affected by the amount of supplementation. Rook et al. (1994) reported that concentrate supplementation, but not pasture height, reduced grazing time 20 min/kg of concentrate. Bite mass decreased as pasture height decreased, while the supplementation amount had no effect on bite mass (Rook et al., 1994). Amount but not type of energy supplement (cereal vs. beet pulp) reduced grazing time 8 to 12 min/kg of concentrate by dairy cows grazing ryegrass at two pasture heights (Kibon and Holmes, 1987). Biting rate was not affected by supplementation amount, type of supplement or pasture height, while bite mass was lower at the low pasture height (Kibon and Holmes, 1987). Recently, Sayers (1999) found that total bites per day and grazing time were higher when cows were supplemented with a fiber-based concentrate than when cows were supplemented with a starch-based concentrate, whereas bite mass was not affected. When the amount of concentrate was increased from 5 to 10 kg/d, total bites/d decreased from 22,023 to 16,933 and grazing time decreased 16 and 20 min/kg of fiber-based or starch-based concentrate, respectively (Sayers, 1999).

Bargo et al. (2002a) reported that supplementation with 7.9 kg/d of a corn-based concentrate reduced grazing time by 75 min/d at low PA and by 104 min/d at high PA. Neither biting rate nor bite mass were affected by treatments. Gibb et al. (2002) reported that as the amount of concentrate supplementation increased from 1.2 to 6.0 kg/d grazing time of dairy cows grazing a ryegrass pasture decreased numerically from 591 to 572 min/d. Supplementation with 2 kg/d of soybean meal did not change any grazing behavior variables of dairy cows grazing a ryegrass pasture fertilized with 0 or 60 kg of N/ha (Delagarde et al., 1997). Bite mass was higher when cows grazed the fertilized pasture (Delagarde et al., 1997). Sayers (1999) studied the effect of amount and CP content of concentrate supplementation on grazing behavior of dairy cows on a ryegrass pasture. None of the grazing behavior variables were affected by the CP content of the concentrate. Total bites per day and grazing time were reduced as the amount of concentrate was increased, but neither the bite mass nor the biting rate changed (Sayers, 1999).

Data from Table 1 show that concentrate supplementation (mean: 4.1 kg/d; range: 2 to 8 kg/d) did not affect biting rate (mean: 58 bites/min; range: 45 to 78 bites/min) or bite mass (mean: 0.46 g of DM/bite; range: 0.27 to 0.64 g of DM/bite) but reduced grazing time by 34

min/d (SE 9 min/d, range: -212 to 25 min/d compared with controls; Student's *t*-test, significantly different from zero, $P < 0.01$) and total bites per day by 2291 (SE 534, range: -6672 to 2833 compared with controls; Student's *t*-test, significantly different from zero, $P < 0.01$). Regression analysis, accounting for the random effect of each study (St-Pierre, 2001), resulted in a negative relationship between grazing time (GT, min/d) and CDMI (kg/d): $GT = 578 \text{ (SE 23)} - 12 \text{ (SE 2) CDMI}$ ($R^2 = 0.88$). Average grazing time for unsupplemented cows is 578 min/d and grazing time is reduced by 12 min/d for every kilogram of concentrate.

SUBSTITUTION RATE AND MILK RESPONSE TO SUPPLEMENTATION

When grazing cows are fed supplements, pasture DMI usually decreases, which is known as substitution rate (SR; Kellaway and Porta, 1993). Substitution rate is calculated as: $SR \text{ (kg/kg)} = (\text{pasture DMI in unsupplemented treatment} - \text{pasture DMI in supplemented treatment}) / \text{supplement DMI}$. A $SR < 1 \text{ kg/kg}$ means that total DMI on the supplemented treatment is higher than total DMI on the unsupplemented treatment. A $SR = 1 \text{ kg/kg}$ means that total DMI on the supplemented treatment is the same than total DMI on the unsupplemented treatment.

Substitution rate is one of the main factors explaining the variation observed in milk response (MR) to supplementation (Kellaway and Porta, 1993; Stockdale, 2000a). Milk response to supplementation is expressed as kg milk/kg supplement, but it can be defined as: 1) overall MR or the increase in kilograms of milk per kilogram of supplement DMI calculated relative to an unsupplemented treatment; and 2) marginal MR or the increase in kilograms of milk per kilogram of incremental increase in supplement DMI calculated for different amounts of supplement. There is usually a negative relationship between SR and MR. When SR is large, resulting in a small increase in total DMI, the MR is low. Milk response in the short-term determines whether supplementation is profitable based on milk and concentrate prices. However, additional long-term factors should also be considered in any economic evaluation, including increase in stocking rates on the farm, improvement in pasture utilization, positive effects on BCS and reproduction, increase in lactation length, and positive effects on milk composition (Kellaway and Porta, 1993).

Because SR and MR are closely related, factors affecting these two variables are discussed together. Substitution rate and MR to supplementation are affected by several pasture, animal, and supplement factors (Stockdale, 2000a; 2000b). The most important pasture-re-

lated factors are PA, pasture height, pasture species, pasture mass, and pasture quality. The most important supplement-related factors are amount and type of supplementation, and the most important animal-related factors are genetic merit of cows, production level, and stage of lactation.

Pasture Allowance

Many studies have reported that SR increases as PA increases (Meijs and Hoekstra, 1984; Stockdale and Trigg, 1985; Stakelum, 1986a, 1986b; Grainger and Matthews, 1989; Robaina et al., 1998; Bargo et al., 2002a). Many of these studies were conducted with low producing cows supplemented with less than 5 kg DM/d of concentrate; only the study of Bargo et al. (2002a) reported high producing cows fed more than 7 kg DM/d of concentrate. When stratifying the treatments in those studies as either low PA (<25 kg DM/cow per day; range: 7.6 to 25 kg DM/cow per day) or high PA (>25 kg DM/cow per day; range: 25 to 42.3 kg DM/cow per day), SR averaged 0.20 kg pasture/kg concentrate (range: 0 to 0.31 kg pasture/kg concentrate) at low PA, and 0.62 kg pasture/kg concentrate (range: 0.55 to 0.69 kg pasture/kg concentrate) at high PA. Considering the study effect as random (St-Pierre, 2001), a significant regression was found between SR (kg pasture/kg concentrate) and PA (kg DM/cow per day): $SR = -0.55 \text{ (SE 0.13)} + 0.05 \text{ (SE 0.009)} PA - 0.0006 \text{ (SE 0.0002)} PA^2$ ($R^2 = 0.94$).

Grazing studies evaluating the effect of PA on SR and MR of high producing dairy cows reported that SR increased and MR decreased as PA increased (Table 2). All those studies showed a negative relationship between MR and SR (Figure 1). Considering the variation due to each study (St-Pierre, 2001), the data from those experiments showed a negative relationship between MR (kg milk/kg concentrate) and SR (kg pasture/kg concentrate): $MR = 1.71 \text{ (SE 0.29)} - 2.01 \text{ (SE 0.66)} SR$ ($R^2 = 0.43$), indicating that the lower the SR the higher the MR expected. This is in agreement with Stockdale (2000b), who summarized data from 20 grazing experiments and reported that MR was negatively related with SR. Higher SR observed when cows grazed at high PA may be partially explained by the higher quality of pasture actually consumed (Dixon and Stockdale, 1999). Because cows grazing at high PA have the opportunity to be more selective, pasture actually eaten has higher digestibility than at low PA (Mayne and Wright, 1988).

Level of Supplementation: Substitution Rate and Milk Response

Grazing studies conducted with high producing dairy cows have shown an inconsistent relationship between

the amount of supplement and the MR and SR (Table 2). Kellaway and Porta (1993) have suggested that SR increases with the amount of concentrate. Peyraud and Delaby (2001), however, reported that in the range of 2 to 6 kg DM/d, amount of concentrate had no consistent effect on SR. Over four studies, three studies had a negative relationship between MR and SR. In contrast, Dillon et al. (1997) reported results from 2 yr showing reductions in SR and MR for cows grazing ryegrass pasture when the amount of supplementation was increased from 2 to 4 kg DM/d.

Accounting for the random effect of study (St-Pierre, 2001), analysis of the data from the four experiments resulted in no relationship between MR and SR, as indicated by the following nonsignificant linear equation: $MR = 0.95 \text{ (SE 0.25)} - 0.28 \text{ (SE 0.51)} SR$ ($R^2 = 0.02$). Based on those studies, the type of relationship between MR and SR when high producing dairy cows on pasture are supplemented with increasing amounts of concentrate is not clear. The lack of a consistent relationship could be attributed to the fact that only few grazing studies have focused on MR with different amounts of concentrate (Peyraud and Delaby, 2001).

Level of Supplementation: Marginal and Overall Milk Response

The marginal MR to increasing amounts of concentrate has been described as curvilinear; i.e., the marginal increase in milk per kilogram of concentrate decreases as the amount of concentrate increases (Kellaway and Porta, 1993). Marginal MR decreased above 3 to 4 kg DM/d of concentrate in some studies, but this is not consistent and occurred primarily when pasture quality and quantity were not limiting and with cows of moderate genetic merit (Peyraud and Delaby, 2001). The response in milk production of high producing dairy cows grazing pasture and supplemented with different amounts of concentrate is shown in Figure 2. The studies were grouped into two categories: 1) those with cows producing more than 28 kg/d at the beginning of the experiment regardless of stage of lactation or with less than 90 DIM, and 2) those with cows producing less than 23 kg of milk/d and more than 160 DIM.

In the first group, cows ranged from 40 to 182 DIM, produced from 28.3 to 45.8 kg/d of milk at the beginning of the experiment, grazed temperate pastures with 39.8 to 56.1% NDF, and the amount of concentrate fed ranged from 0 to 10 kg DM/d. Milk response ranged from 0.60 (Sayers, 1999) to 1.45 kg milk/kg concentrate (Gibb et al., 2002). Combining those five studies and after considering the study random effect (St-Pierre, 2001), the significant linear regression between MY (kg/d) and CDMI (kg/d) was: $MY = 22.20 \text{ (SE 0.87)} + 1.03$

Table 2. Substitution rate (SR) and milk response (MR) of dairy cows supplemented with concentrates.

Reference	Cows ¹		Pasture ²	Supplement		PA ³ kg DM/cow/d	SR ⁴	MR ⁴
	DIM	Milk		Type	DMI, kg/d		kg pasture/ kg concentrate	kg milk/kg concentrate
Effect of PA								
Bargo et al., 2002a	101	45.8	OG	Corn	7.9	25.0	0.26	1.36
						40.0	0.55	0.96
Robaina et al., 1998	180	20.5	RG/WC	Barley/lupin	4.3	21.1	0.31	0.98
						42.3	0.57	0.54
Stockdale, 1999a ⁵	106 to 229	19.3 to 30.6	RG/WC/P	Barley/wheat	3 to 5	30.0	0.43	0.43
						30.0	0.45	0.55
						30.0	0.29	1.18
						30.0	0.30	1.17
						40.0	0.43	0.49
						40.0	0.46	0.98
						40.0	0.31	0.94
Effect of amount of concentrate								
Dillon et al., 1997	31	27.0	RG	Corn/beet pulp	2.0	...	0.46	0.50
					4.0	...	0.18	0.31
				Corn/beet pulp	2.0	...	0.14	0.30
					4.0	...	0.21	0.35
Reis and Combs, 2000b	84	41.6	A/RC/RG	Corn	5.0	...	0.24	1.00
					10.0	...	0.41	0.86
Robaina et al., 1998	180	21.4	RG/WC	Barley	1.8	...	0.44	1.56
					3.4	...	0.65	0.94
					6.7	...	0.58	0.82
Walker et al. 2001	167	22.3	P/RG	Barley/wheat	3.0	...	0.02	1.07
					5.0	...	0.18	1.18
					7.0	...	0.21	1.07
					9.0	...	0.19	0.92
					10.4	...	0.28	0.91
Effect of type of concentrate								
Sayers, 1999	40	NA ⁶	RG	Starch (barley/corn)	10.0	...	0.62	0.68
				Fiber (beet/citrus pulp)	10.0	...	0.50	0.86
Schwarz et al., 1995	49	27	Grass/legume	Starch (corn)	6.1	...	0.49	0.74
(Confinement) ⁷				Fiber (sugar beet pulp)	7.1	...	0.52	0.37
				Starch (corn)	4.5	...	0.27	0.76
				Fiber (sugar beet pulp)	5.2	...	0.31	0.42
Spörndly, 1991	175	25.7	Grass	Starch (barley)	3.3	...	0.54	0.24
(Confinement) ⁷				Fiber (beet pulp)	3.3	...	0.64	0.06
				Starch (barley)	5.8	...	0.60	0.40
				Fiber (beet pulp)	5.6	...	0.71	0.41

¹Pre-experimental DIM and milk production (kg/d).²A = alfalfa (*Medicago sativa*); OG = orchardgrass (*Dactylis glomerata*); P = (*Paspalum dilatatum*); RC = red clover (*Trifolium pratense*); RG = perennial ryegrass (*Lolium perenne*); WC = white clover (*Trifolium repens*).³PA = pasture allowance.⁴Calculated relative to the unsupplemented treatment.⁵Data from 7 experiments.⁶Not available.⁷In confinement studies, fresh-cut forage was used instead of grazed pasture.

Figure 1. Relationship between milk response (MR) and substitution rate (SR) by grazing dairy cows supplemented with concentrate on studies evaluating the effect of pasture allowance (● Bargo et al., 2002a; □ Robaina et al., 1998; ■ Stockdale, 1999a).

(SE 0.06) CDMI ($R^2 = 0.95$), indicating an overall MR of 1 kg milk/kg concentrate (Figure 2). In the second group, cows ranged from 180 to 211 DIM, produced from 19.4 to 22.3 kg/d of milk at the beginning of the experiment, grazed temperate pastures with 53.7 to 64.8% NDF, and amount of concentrate fed ranged from

Figure 2. Relationship between milk production (MP) and concentrate DMI (CDMI) by grazing dairy cows supplemented with different amounts of concentrate (■ studies with cows < 90 DIM or > 28 kg milk/d at the beginning of the experiment; Bargo et al., 2002a; Delaby et al., 2001; Gibb et al., 2002; Reis and Combs, 2000b; Sayers, 1999; □ studies with cows > 160 DIM or < 23 kg milk/d at the beginning of the experiment; Robaina et al., 1998; Sayers, 1999; Walker et al., 2001). Close and open squares correspond to actual values, regression lines correspond to parameters estimated after adjusting for study effect (St-Pierre, 2001).

0 to 10.4 kg DM/d. Milk response ranged from 0.76 (Robaina et al., 1998) to 1.09 kg milk/kg concentrate (Sayers, 1999). Combining those three studies and accounting for the random effect of each (St-Pierre, 2001), a significant quadratic regression was found between MY (kg/d) and (CDMI kg/d): $MY = 12.92 \text{ (SE 0.36)} + 1.23 \text{ (SE 0.16) CDMI} - 0.04 \text{ (SE 0.02) CDMI}^2$ ($R^2 = 0.94$), indicating a decrease in marginal MR as the concentrate DMI increased (Figure 2).

The intercepts (12.9 vs. 22.4 kg/d) in Figure 2 show the differences in stage of lactation and may also indicate differences in genetic merit between the two groups; however, these two factors are confounded. From this figure it can be concluded that milk production of high producing dairy cows in early lactation increases linearly as the amount of concentrate increases from 1.8 to 10 kg DM/d with an overall MR of 1 kg milk/kg concentrate. Milk production of high producing dairy cows in late lactation, however, increases as the amount of concentrate increase cows but with a lower marginal MR per kilogram of concentrate. To avoid metabolic health problems such as acidosis or subclinical acidosis, it is not recommended to supplement more than about 10 kg DM/d (or >50% of the total diet DMI). At that limit, decreased marginal MR traditionally observed when supplementation is increased did not occur with high producing cows. Another factor that needs to be considered is the pasture quality. The NDF was >50% in several studies, suggesting that high fiber intake may allow for feeding high amounts of concentrate.

Previous reviews (Journet and Demarquilly, 1979) reported average MR from 0.4 to 0.6 kg milk/kg concentrate. However, recently Peyraud and Delaby (2001) reported that the MR to concentrate was higher than previously reported research in the literature published after 1990, which can be attributed to the increase in genetic merit of cows. A greater response to supplementation may be expected in high genetic merit cows because they partition more nutrients to milk production and lose more BW in early lactation than low genetic merit cows (Kellaway and Porta, 1993). Stage of lactation also influences lactational responses to concentrate supplements (Dixon and Stockdale, 1999). In early lactation, cows partition more nutrients toward milk production, thus MR to supplementation may be higher than in late lactation, when more nutrients are directed to BW (Kellaway and Porta, 1993). The average milk yield response to concentrate supplementation of grazing cows supplemented with 3 kg DM/d concentrate was 0.7, 0.4, 0.5, and 0 kg milk/kg concentrate when they were between 86 to 114, 115 to 133, 134 to 187, and 188 to 243 DIM, respectively (O'Brien et al., 1999). Summarizing five experiments with supplement DMI

from 0 to 7 kg/d, the marginal MR was 1.3, 1.1, and 0.7 kg milk/kg supplement in early, mid, and late lactation (Stockdale et al., 1987).

Type of Supplement

The type of supplement influences SR and animal performance (Stockdale, 2000b). Forage supplementation decreases pasture DMI more than concentrates (Mayne and Wright, 1988). Including both low and high PA, SR ranged from 0.84 to 1.02 kg/kg for grass silage supplementation and from 0.11 to 0.50 kg/kg for concentrate supplementation (Mayne and Wright, 1988). Recently, Stockdale (2000b) reviewed 39 datasets from grazing studies and concluded that supplementation with forages, such as hay or corn silage, resulted in higher SR than supplementation with concentrates. Stockdale (1999b) found, however, that SR were similar when dairy cows grazing a ryegrass/white clover pasture were supplemented with grain or hay, which shows that the effects of supplement type on SR may not occur if both PA and amount of supplementation are low.

Meijs (1986) reported that SR was reduced from 0.45 kg pasture/kg high-starch concentrate to 0.21 kg pasture/kg fiber-based concentrate when cows grazed a ryegrass pasture. Studies with high producing dairy cows grazing or fed fresh-cut forage in confinement evaluated the effect of type of concentrate (starch vs. fiber-based) on SR and MR (Table 2). Two studies (Schwarz et al., 1995; Sayers, 1999) had a negative relationship between MR and SR, while the third study (Spörndly, 1991) had a positive relationship. In the studies of Schwarz et al. (1995) and Spörndly (1991), however, the effect of type of concentrate is confounded with the effect of the amount fed because two amounts of each type of concentrate were fed. They were also conducted in confinement, a condition in which SR may differ from grazing studies. Combining the data from these three experiments and accounting for the random effect of each study (St-Pierre, 2001), no general relationship was found between MR and SR, as indicated by the following nonsignificant linear equation: $MR = 0.75 (SE\ 0.36) - 0.43 (SE\ 0.64) SR$ ($R^2 = 0.53$). Based on those three studies, there is not enough information in the literature to conclude the type of relationship between MR and SR when high producing dairy cows on pasture are supplemented with starch or fiber-based concentrates.

Causes of Substitution Rate

It has been hypothesized that SR is caused by negative associative effects in the rumen (Dixon and Stockdale, 1999), or reduction in grazing time (McGilloway

and Mayne, 1996). When concentrate supplements are included in pasture diets, associative effects may occur if digestive and metabolic interactions between them change the intake of energy (Dixon and Stockdale, 1999). An increase in total digestibility may be expected with the inclusion of concentrates in the diet because they are usually higher in digestibility than pasture. However, interactions between the digestion of concentrates and pasture may reduce fiber digestion (Dixon and Stockdale, 1999). The energy provided by the concentrate (fermentable carbohydrates) may lead to reductions in ruminal pH, which may decrease the activity or number of cellulolytic bacteria, reduce the rate of fiber digestion of pasture, and therefore pasture DMI (Dixon and Stockdale, 1999). Based on this hypothesis, small amounts of concentrate supplementation or supplementation with concentrates with a slow rate of degradation would result in lower SR (Kellaway and Porta, 1993). However, studies on the effect of amount of concentrate supplementation on SR (Table 2) did not show a clear trend to lower SR with small amounts of concentrate, probably because of the small number of studies. Under the same hypothesis, concentrates that are more slowly degraded in the rumen (e.g., fiber-based concentrates) would minimize SR compared with concentrates that are more rapidly degraded in the rumen (e.g., starch-based concentrates) because ruminal pH would be higher with fiber-based concentrates. However, the effect of the type of concentrate (Table 2) showed inconsistent results, which may be related to the different sources and proportion of starch and fiber that determines the rate of ruminal degradation. More information is needed related to the type and amount of concentrate supplementation and their interaction on SR of high producing dairy cows on pasture.

The second hypothesis proposed to explain SR is related to grazing time. It has been suggested that reductions in grazing time by supplementation would explain SR (Mayne and Wright, 1988; McGilloway and Mayne, 1996). A significant negative relationship was presented and discussed above between grazing time and concentrate DMI, which indicates a reduction of 12 min/d per kilogram of concentrate.

Bargo et al. (2002a) studied ruminal digestion and grazing time of high producing dairy cows grazing at low and high PA to test both hypotheses on SR. Substitution rate was higher (0.55 vs. 0.26 kg pasture/kg concentrate) when supplemented cows grazed at higher PA (40 vs. 25 kg of DM/cow per day), and it was related to both negative associative effects in the rumen and reduction in grazing time. Supplementation with 7.9 kg/d of a corn-based concentrate reduced ruminal pH, ruminal degradation rate of pasture, and fiber digestibility at both PA (Bargo et al., 2002a). Grazing time

was reduced 75 min/d, with supplementation at the low PA, which explained nearly all of the 2.0 kg/d reduction in pasture DMI measured by Cr_2O_3 ($75 \text{ min/d} \times 55 \text{ bites/min} \times 0.55 \text{ g of DM/bite} = 2.3 \text{ kg/d}$). At the high PA, concentrate supplementation reduced grazing time 104 min/d and explained 80% of the 4.4 kg/d reduction in pasture DMI ($104 \text{ min/d} \times 56 \text{ bites/min} \times 0.60 \text{ g of DM/bite} = 3.5 \text{ kg}$). The remaining 20% may be related to negative associative effects in the rumen; for example, the decrease in apparent digestibility of NDF by concentrate supplementation was greater at the high PA than at the low PA (4.3 vs. 1.1 percentage points, respectively; Bargo et al., 2002a).

EFFECT OF SUPPLEMENTATION ON DRY MATTER INTAKE, MILK PRODUCTION, AND MILK COMPOSITION

Energy Supplementation

Level of supplementation. Studies conducted with high producing dairy cows on pasture that have evaluated the effect of amount of concentrate supplementation on DMI, and milk production and composition are presented in Table 2. Overall, pasture DMI decreased and total DMI increased by increasing the amount of concentrate. Pasture DMI was numerically (Arriaga-Jordan and Holmes, 1986; Dillon et al., 1997) or significantly (Spörndly, 1991; Robaina et al., 1998; Sayers, 1999; Reis and Combs, 2000b; Walker et al., 2001; Bargo et al., 2002a) reduced when amount of concentrate increased, which is related to the SR. For the range of concentrate supplementation (1.8 to 10.4 kg DM/cow per day), pasture DMI decreased 1.9 kg/d (SE 0.3 kg/d, range: -0.1 to -4.4 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) or 13% compared with pasture DMI of pasture-only diet treatments (14.8 kg/d). When corrected for the random effect of study (St-Pierre, 2001), a significant negative relationship was found between pasture DMI reduction (**PDMI_r**, kg/d) and CDMI (kg/d): $\text{PDMI}_r = 0.26 \text{ (SE 0.54)} - 0.39 \text{ (SE 0.07) CDMI}$ ($R^2 = 0.82$). Total DMI was numerically (Arriaga-Jordan and Holmes, 1986) or significantly (Spörndly, 1991; Dillon et al., 1994; Robaina et al., 1998; Sayers, 1999; Reis and Combs, 2000b; Walker et al., 2001; Bargo et al., 2002a) increased 3.6 kg/d (SE 0.5 kg/d, range: 1.0 to 7.5 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) or 24% compared with total DMI of pasture-only diet treatments. When corrected for the random effect of study (St-Pierre, 2001), a significant positive relationship was found between total DMI increase (**TDMI_i**, kg/d) and CDMI (kg/d): $\text{TDMI}_i = 0.08 \text{ (SE 0.73)} + 0.52 \text{ (SE 0.08) CDMI}$ ($R^2 = 0.91$).

The studies presented in Table 3 reported that milk production increase averaged 4.4 kg/d (SE 0.6 kg/d, range: 0.8 to 10.6 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) with the amount of supplementation or 22% compared with the pasture-only diet treatments (19.7 kg/d). When corrected for the random effect of study (St-Pierre, 2001), a significant positive relationship was found between milk production increase (**MP_i**, kg/d) and CDMI (kg/d) and TDMI_i (kg/d): $\text{MP}_i = 0.09 \text{ (SE 0.65)} + 0.26 \text{ (SE 0.12) CDMI} + 0.89 \text{ (SE 0.19) TDMI}_i$ ($R^2 = 0.98$).

Most of the studies showed that milk fat percentage decreased when the amount of concentrate was increased (Arriaga-Jordan and Holmes, 1986; Spörndly, 1991; Sayers, 1999; Reis and Combs, 2000b; Valentine et al., 2000; Walker et al., 2001; Bargo et al., 2002a). Other studies, however, showed no changes (Hoden et al., 1991; Wilkins et al., 1994; Dillon et al., 1997; Robaina et al., 1998). Overall, the reduction in fat percentage averaged 0.24 percentage units (SE 0.07 percentage units, range: -1.23 to 0.22 percentage units; Student's *t*-test, significantly different from zero, $P < 0.01$) or 6% compared with the pasture-only diet treatments (4.04%). When corrected for the random effect of study (St-Pierre, 2001), a significant negative relationship was found between fat percentage reduction (**FPr**), CDMI (kg/d), and PDMI_r (kg/d): $\text{FPr} = 0.25 \text{ (SE 0.11)} - 0.13 \text{ (SE 0.02) CDMI} - 0.11 \text{ (SE 0.05) PDMI}_r$ ($R^2 = 0.71$). Fat yield, however, increased numerically (Arriaga-Jordan and Holmes, 1986; Hoden et al., 1991; Spörndly, 1991; Dillon et al., 1997; Robaina et al., 1998; Valentine et al., 2000; Walker et al., 2001) or significantly (Hoden et al., 1991; Wilkins et al., 1994; Reis and Combs, 2000b; Bargo et al., 2002a) with supplementation: 0.10 kg/d (SE 0.02 kg/d, range: -0.13 to 0.31 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) or 13% compared with the pasture-only diet treatments (0.77 kg/d). When corrected for the random effect of study (St-Pierre, 2001), a significant positive relationship was found between fat yield increase (**FY_i**, kg/d) and TDMI_i (kg/d): $\text{FY}_i = 0.003 \text{ (SE 0.05)} + 0.02 \text{ (SE 0.01) TDMI}_i$ ($R^2 = 0.78$).

Several authors reported that increasing the amount of concentrate supplementation increased milk protein percentage (Hoden et al., 1991; Spörndly, 1991; Wilkins et al., 1994; Sayers, 1999; Reis and Combs, 2000b; Valentine et al., 2000; Bargo et al., 2002a). Linear increases in milk protein percentage have been reported for a wide range of amounts of supplementation, including 0 to 4 kg DM/d (Hoden et al., 1991; Wilkins et al., 1994), 0 to 10 kg DM/d (Reis and Combs, 2000b), and 7 to 13 kg DM/d (Valentine et al., 2000). Other studies, however, found no changes in milk protein percentage within a range of supplementation from 0 to 3.6 kg DM/d (Dillon

Table 3. Effect of amount of concentrate supplementation on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹		Pasture ²	Concentrate ³	DMI, kg/d			Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d
	DIM	Milk			Supplement	Pasture	Total					
Arriaga-Jordan and Holmes, 1986 ⁴	72	37.8	RG (rotational) ⁵	Barley	0.7	15.3	16.0	29.4	3.73 ^a	NA ⁶	1.10	NA
					4.7	14.7	19.4	31.9	3.51 ^a	NA	1.12	NA
			RG (continuous) ⁵	Barley	0.7	18.1	18.8	30.2 ^a	3.64 ^a	NA	1.10	NA
					4.7	16.5	21.2	32.8 ^b	3.40 ^b	NA	1.12	NA
Bargo et al., 2002a	101	45.8	OG (low allowance)	Mineral/vitamin Corn	0.8	17.5 ^b	18.3 ^a	19.1 ^a	3.82 ^a	2.98 ^a	0.74 ^a	0.55 ^a
					8.6	15.5 ^a	24.1 ^c	29.7 ^c	3.29 ^b	3.08 ^b	0.96 ^c	0.89 ^c
			OG (high allowance)	Mineral/vitamin Corn	0.7	20.5 ^c	21.2 ^b	22.2 ^b	3.79 ^a	2.93 ^a	0.84 ^b	0.64 ^b
					8.7	16.1 ^a	24.8 ^c	29.9 ^c	3.32 ^b	3.11 ^b	0.98 ^c	0.90 ^c
Hoden et al., 1991	49	30.2	RG	Corn/beet pulp	0.5	NA	NA	20.7 ^a	3.78	3.03 ^a	0.78 ^a	0.62 ^a
					3.7	NA	NA	22.6 ^b	3.76	3.09 ^b	0.85 ^b	0.69 ^b
Dillon et al., 1997	31	27	RG	Corn/beet pulp	0.0	17.1	17.1 ^a	24.0 ^a	3.71	3.25	0.88	0.77 ^a
					1.8	16.5	18.3 ^b	25.0 ^b	3.68	3.28	0.90	0.82 ^b
					3.6	16.8	20.4 ^c	26.6 ^c	3.55	3.26	0.93	0.86 ^c
Reis and Combs, 2000b	84	41.6	A/RC/RG	Corn	0.0	13.9 ^a	13.9 ^a	21.8 ^a	3.89 ^a	2.85 ^a	0.88 ^a	0.62 ^a
					5.0	12.7 ^b	17.7 ^b	26.8 ^b	3.50 ^b	2.95 ^b	0.83 ^{ab}	0.79 ^b
					10.0	9.8 ^c	19.8 ^c	30.4 ^c	3.08 ^c	3.05 ^c	0.75 ^b	0.93 ^c
Robaina et al., 1998	180	21.4	RG/WC	Barley	0.0	14.3 ^a	14.3 ^a	12.9 ^a	4.33	3.10 ^a	0.55	0.39
					1.8	13.5 ^b	15.3 ^b	15.7 ^b	4.33	3.19 ^b	0.67	0.49
					3.4	12.1 ^c	15.5 ^c	16.1 ^c	4.36	3.17 ^b	0.68	0.50
					6.7	10.4 ^d	17.1 ^d	18.4 ^d	4.36	3.29 ^b	0.78	0.59
Sayers, 1999	40	NA ⁶	RG	Barley/wheat/corn	5.0	12.6 ^a	17.6 ^a	31.2 ^a	3.66 ^a	3.37 ^a	1.12	1.04 ^a
					10.0	9.5 ^b	19.4 ^b	34.6 ^b	2.99 ^b	3.55 ^b	1.04	1.22 ^b
Spörndly, 1991 (Confinement) ⁷	175	25.7	Grass	Barley	0.0 + 2 (hay)	14.6 ^a	16.5 ^a	19.7 ^a	4.46 ^a	3.28 ^a	0.88	0.65
					3.3 + 2 (hay)	12.7 ^b	18.0 ^b	20.5 ^{ab}	4.68 ^b	3.39 ^b	0.96	0.69
					5.8 + 2 (hay)	11.0 ^c	18.8 ^c	22.0 ^b	4.44 ^a	3.50 ^c	0.98	0.77
Valentine et al., 2000	41	NA	RG/RC	Barley	7.0	NA	NA	26.4 ^a	3.59 ^a	2.97 ^a	0.93	0.78 ^a
					10.0	NA	NA	28.0 ^b	3.47 ^a	3.06 ^b	0.97	0.86 ^b
					13.0	NA	NA	28.7 ^b	3.20 ^b	3.10 ^c	0.92	0.88 ^b
Walker et al., 2001	167	22.3	P/RG	Barley/wheat	0.0	12.1 ^d	12.1 ^a	12.4 ^a	4.48 ^b	3.16	0.56	0.39
					3.0	12.0 ^d	15.0 ^b	15.6 ^b	4.21 ^b	3.33	0.66	0.52
					5.0	11.2 ^c	16.2 ^c	18.3 ^c	4.09 ^b	3.33	0.75	0.61
					7.0	10.6 ^{bc}	17.6 ^d	19.9 ^{cd}	4.05 ^b	3.30	0.81	0.66
					9.0	10.4 ^b	19.3 ^e	20.7 ^d	4.18 ^b	3.35	0.87	0.69
					10.4	9.2 ^a	19.6 ^e	21.9 ^d	3.25 ^a	3.41	0.71	0.75
Wilkins et al., 1994	41	NA	RG/WC	NA	0.0	NA	NA	22.9 ^a	3.69	2.79 ^a	0.83 ^a	0.64 ^a
					2.0	NA	NA	25.9 ^b	3.78	2.85 ^b	0.98 ^b	0.73 ^b
					4.0	NA	NA	26.0 ^b	3.87	2.94 ^c	1.00 ^b	0.76 ^c

^{a,b,c}Means within reference with different superscripts differ ($P < 0.05$).

¹Pre-experimental DIM and milk production (kg/d).

²A= alfalfa (*Medicago sativa*); OG = orchardgrass (*Dactylis glomerata*); P = paspalum (*Paspalum dilatatum*); RC = red clover (*Trifolium pratense*); RG = perennial ryegrass (*Lolium perenne*); WC = white clover (*Trifolium repens*).

³Main energy source in the concentrate.

⁴OM intake.

⁵Grazing system.

⁶Not available.

⁷In confinement studies, fresh-cut forage was used instead of grazed pasture.

et al., 1997) and 0 to 10.4 kg DM/d (Walker et al., 2001). Overall, the increase in protein percentage averaged 0.13 percentage units (SE 0.01 percentage units, range: 0.01 to 0.25 percentage units; Student's *t*-test, significantly different from zero, $P < 0.01$) or 4% compared to the pasture-only diet treatments (3.06%). When corrected for the random effect of study (St-Pierre, 2001), a significant positive relationship was found between protein percentage increase (**PPi**) and CDMI (kg/d): $PPi = 0.05$ (SE 0.03) + 0.01 (SE 0.003) CDMI ($R^2 = 0.72$). Protein yield was increased numerically (Spörndly, 1991; Robaina et al., 1998; Walker et al., 2001) or significantly (Hoden et al., 1991; Wilkins et al., 1994; Dillon et al., 1997; Reis and Combs, 2000b; Valentine et al., 2000; Bargo et al., 2002a) with supplementation: 0.17 kg/d (SE 0.02 kg/d, range: 0.04 to 0.36 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) or 30% compared with the pasture-only diet treatments (0.56 kg/d). When corrected for the random effect of study (St-Pierre, 2001), a significant positive relationship was found between protein yield increase (**PYi**, kg/d) and CDMI (kg/d) and TDMIi (kg/d): $PYi = 0.01$ (SE 0.02) + 0.01 (SE 0.004) CDMI + 0.03 (SE 0.006) TDMIi ($R^2 = 0.96$).

Starch vs. fiber-based concentrates. Studies comparing starch or fiber-based concentrates for high producing dairy cows on pasture are presented in Table 4. Some of those were grazing studies (Meijs, 1986; Sayers, 1999; Delahoy et al., 2003), and others were confinement studies with cows fed fresh-cut forage (Garnsworthy, 1990; Valk et al., 1990; Spörndly, 1991; Schwarz et al., 1995). Sources of starch included corn (Schwarz et al., 1995; Valk et al., 2000; Delahoy et al., 2003), barley (Spörndly, 1991), cassava (Meijs, 1986), or the combination of barley, wheat, and corn (Garnsworthy, 1990; Sayers, 1999). Sources of fiber included oatfeed (Garnsworthy, 1990), and beet pulp either alone (Spörndly, 1991; Schwarz et al., 1995; Valk et al., 2000) or combined with soy hulls (Meijs, 1986; Delahoy et al., 2003) or citrus pulp (Sayers, 1999). Because starch sources are more commonly used to supplement dairy cows on pasture than fiber sources, results of these studies are summarized as the effect of fiber-based concentrate compared to starch-based concentrates.

In the grazing studies, pasture and total DMI were increased 0.7 (Meijs, 1986) and 0.8 kg/d (Sayers, 1999) when fiber-based concentrates replaced starch-based concentrates for early lactation cows grazing ryegrass pastures. For late-lactation cows grazing orchardgrass, pasture and total DMI were similar with both types of concentrates (Delahoy et al., 2003). Confinement studies reported similar fresh-cut forage DMI (Spörndly, 1991; Schwarz et al., 1995; Valk et al., 2000) and similar (Spörndly, 1991; Schwarz et al., 1995) or lower (Valk

et al., 2000) total DMI. The low number of studies do not allow for strong conclusions, but compared with starch-based concentrates, fiber-based concentrates increased pasture DMI 0.7 kg/d (range: -0.1 to 1.4 kg/d) in grazing studies, and reduced pasture DMI 0.45 kg/d (range: -0.3 to -0.7 kg/d) in confinement studies. Overall, fiber-based concentrates slightly increased pasture DMI 0.13 kg/d, with a large variation among studies (range: -0.7 to 1.4 kg/d).

Milk production was increased when fiber-based concentrates replaced starch-based concentrates in only one grazing study (Meijs, 1986), while two grazing studies reported similar milk production (Sayers, 1999; Delahoy et al., 2003). In the confinement studies, milk production was not affected (Garnsworthy, 1990; Spörndly, 1991; Schwarz et al., 1995) or was reduced (Valk et al., 1990) by fiber-based concentrates compared to starch-based concentrates. The higher milk production with starch-based concentrates in the study of Valk et al. (1990) could be attributed to the higher total DM and energy intake in that treatment. Overall, milk production was slightly reduced (-0.46 kg/d) when fiber-based concentrates replaced starch-based concentrates, but the range of variation is large (-2.6 to 1.3 kg/d).

Most of the studies (Meijs, 1986; Garnsworthy, 1990; Valk et al., 1990; Schwarz et al., 1995; Delahoy et al., 2003) did not report changes in milk fat percentage. However, Sayers (1999) reported higher fat percentage with fiber-based than with starch-based concentrates, particularly when large amounts of concentrate (10 kg DM/d) were supplemented to cows grazing a ryegrass pasture. In contrast, Spörndly (1991) found that in confinement, fiber-based concentrates reduced milk fat content. However, in that study, cows consumed 2 kg DM/d of hay, which makes comparison between the studies difficult. Replacing starch-based by fiber-based concentrates reduced significantly (Spörndly, 1991; Sayers, 1999; Delahoy et al., 2003) and numerically (Meijs, 1986; Valk et al., 1990; Schwarz et al., 1995) milk protein percentage. Overall, milk protein percentage was reduced -0.06 percentage units (range: -0.21 to 0.05 percentage units) with fiber-based concentrates compared with starch-based concentrates.

The number of studies in which fiber-based concentrates replaced starch-based concentrates is too small to make strong conclusions, and half of the studies were conducted in confinement. Inconsistency in the results can also be attributed to differences in the source of starch or fiber used in the concentrate, type of pasture, and other components in the diet, all factors that may affect the rate of degradation of concentrates in the rumen. Meijs (1986) suggested that supplementing a highly degradable pasture with a starch-based concentrate might reduce ruminal pH and pasture ruminal

Table 4. Effect of starch (S) or fiber (F)-based concentrate supplementation on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹		Pasture ²	Concentrate type ³	DMI, kg/d			Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d
	DIM	Milk			Supplement	Pasture	Total					
Delahoy et al., 2003	182	35.5	OG	S (corn)	8.2	12.1	20.3	27.6	3.53	3.23 ^a	1.05	0.96
				F (beet pulp/soy hulls)	8.2	12.0	20.2	27.4	3.63	3.19 ^b	1.08	0.95
Garnsworthy, 1990	NA ⁴	NA	Perennial grass	S (barley/corn)	4.0	NA	NA	21.3	3.99	3.44	0.85	0.73
				F (oatfeed)	4.0	NA	NA	22.9	4.27	3.48	0.98	0.79
Meijs, 1986 ⁵	60	28.9	RG	S (cassava/corn)	5.5	11.7 ^a	17.2 ^a	25.6 ^a	3.96	3.40	1.01 ^a	0.87
				F (beet pulp/soybean hulls)	5.4	12.4 ^b	17.8 ^b	26.9 ^b	4.10	3.37	1.09 ^b	0.90
Sayers, 1999	40	NA	RG	S (barley/wheat/corn)	5.0	12.6 ^a	17.6 ^a	31.2 ^a	3.66 ^a	3.37 ^a	1.12 ^a	1.04 ^a
				F (beet pulp/citrus pulp)	5.0	13.4 ^b	18.4 ^b	30.9 ^a	3.94 ^b	3.30 ^b	1.18 ^b	1.00 ^b
				S (barley/wheat/corn)	10.0	9.5 ^c	19.4 ^c	34.6 ^b	2.99 ^c	3.55 ^c	1.04 ^a	1.22 ^c
				F (beet pulp/citrus pulp)	10.0	10.9 ^d	20.8 ^d	35.2 ^b	3.62 ^a	3.34 ^a	1.26 ^b	1.17 ^d
Schwarz et al., 1995 (Confinement) ⁶	56	28.2	Grass/legumes	Control	0.0 + 0.15 (minerals)	14.9 ^a	15.0 ^a	20.3 ^b	4.16	3.13	0.85	0.62 ^a
				S (corn)	6.1 + 0.15 (minerals)	11.9 ^b	18.2 ^b	24.8 ^a	3.69	3.23	0.90	0.79 ^b
				F (molassed sugar beet pulp)	7.1 + 0.15 (minerals)	11.2 ^b	18.5 ^b	22.9 ^{ab}	3.90	3.16	0.89	0.72 ^b
Spörndly, 1991 (Confinement) ⁶	175	25.7	Grass	Control	0.0 + 1.9 (hay)	14.6 ^a	16.5 ^a	19.7 ^a	4.46 ^{ac}	3.28 ^a	0.88	0.65
				S (barley)	3.3 + 2 (hay)	12.7 ^b	18.0 ^b	20.5 ^{ab}	4.68 ^b	3.39 ^b	0.96	0.69
				F (beet pulp)	3.3 + 2 (hay)	12.4 ^b	17.7 ^b	19.9 ^a	4.50 ^a	3.44 ^{bc}	0.90	0.68
				S (barley)	5.8 + 2 (hay)	11.0 ^c	18.8 ^c	22.0 ^b	4.44 ^{ac}	3.50 ^c	0.98	0.77
				F (beet pulp)	5.6 + 2 (hay)	10.5 ^c	18.1 ^{bc}	22.0 ^b	4.32 ^c	3.41 ^b	0.95	0.75
Valk et al., 1990 (Confinement) ⁶	83	34.6	RG	S (corn)	5.6 + 1.5(Cr ₂ O ₃ pellets)	11.2	18.3 ^a	28.4 ^a	3.92	3.48	1.11	0.98 ^a
				F (beet pulp)	5.4 + 1.4(Cr ₂ O ₃ pellets)	10.9	17.7 ^b	25.8 ^b	4.15	3.43	1.07	0.89 ^b

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$; unless otherwise stated; Meijs, 1986, $P < 0.10$ for milk; Sayers, 1999 interaction significant for fat and protein content).

¹Pre-experimental DIM and milk production (kg/d).

²OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*).

³Between parentheses main starch or fiber source used in the concentrate.

⁴Not available.

⁵OM intake.

⁶In confinement studies, fresh cut-forage was used instead of grazed pasture.

digestion, increase retention time of feed in the rumen, and decrease pasture DMI. Replacing starch-based concentrates with fiber-based concentrates would maintain higher pH in the rumen, enhance pasture digestion, and result in higher DMI. In the studies of Meijs (1986) and Sayers (1999) both pasture (ryegrass) and starch (cassava or barley plus wheat) were highly degradable in the rumen and could explain the response in DMI with fiber-based concentrate. In the study of Spörndly (1991), the inclusion of hay in the diet may have maintained a higher pH in the rumen and therefore explain similar DMI even with highly degradable starch source such as barley. The use of a starch source with lower degradability than barley such as corn (Schwarz et al., 1995; Delahoy et al., 2003) may not be as detrimental to ruminal pH and may explain similar pasture DMI observed in those studies with cows grazing a slowly degradable pasture of orchardgrass (Delahoy et al., 2003).

Processed grain. Processing methods for grains used for dairy cows have been extensively reviewed (Theurer et al., 1999); however, that review focused on cows fed TMR diets in confinement. Studies evaluating the effect of processed grains such as corn or sorghum on DMI, and milk production and composition of dairy cows on pasture are presented in Table 5. Seven of those eight studies were grazing studies (Bargo et al., 1998; Pieroni et al., 1999; Reis and Combs, 2000a; Soriano et al., 2000; Alvarez et al., 2001; Wu et al., 2001; Delahoy et al., 2003), and one was conducted in confinement with fresh-cut forage (Reis et al., 2001). Results are summarized as the effect of forms of processing compared with unprocessed (dry) forms. Forms of processing included high moisture corn (Soriano et al., 2000; Alvarez et al., 2001; Reis et al., 2001; Wu et al., 2001), steam-flaked corn with a density of 290 (Bargo et al., 1998) or 360 g/L (Delahoy et al., 2003), steam-rolled corn with a density of 591 g/L (Reis and Combs, 2000a), and steam-flaked sorghum with a density of 480 g/L (Pieroni et al., 1999).

Four of the five studies did not report differences in pasture or total DMI when dry corn was replaced by processed corn (Reis and Combs, 2000a; Alvarez et al., 2001; Reis et al., 2001; Delahoy et al., 2003). For sorghum grain, however, Pieroni et al. (1999) reported higher pasture and total DMI with steam-flaked grain than with dry ground grain. Except for Wu et al. (2001), none of the studies reported an increase in milk production when steam processed or high-moisture grains replaced dry grains. Supplementation with finely ground high moisture corn instead of dry cracked shelled corn increased milk production in late lactation dairy cows grazing grass/legume pasture (Wu et al., 2001). Overall, the average milk production difference between pro-

cessed and unprocessed grains was small (mean 0.06 kg/d, range: -1.6 to 2.4 kg/d), indicating that similar milk production can be expected.

Compared with unprocessed grains, supplementation with processed grains did not change milk fat percentage in seven of eight studies (Bargo et al., 1998; Pieroni et al., 1999; Reis and Combs, 2000a; Soriano et al., 2000; Alvarez et al., 2001; Delahoy et al., 2003; Reis et al., 2001); only Wu et al. (2001) reported a reduction in milk fat content. Only two of the eight studies (Alvarez et al., 2001; Wu et al., 2001) found higher milk protein percentage with high moisture corn than with dry corn. Increase in milk protein content averaged 3% (0.09 to 0.11 percentage units), which may suggest an increase in ruminal available energy with processed corn. Overall, the replacement of unprocessed by processed grains resulted in small changes in milk fat (mean: -0.06 percentage units, range: -0.39 to 0.16 percentage units) and protein (mean: 0.04 percentage units, range: -0.03 to 0.11 percentage units) content in milk.

Although the number of studies is not large enough to make strong conclusions, the lack of response to processed grains can be related to changes only in site of digestion (i.e., more energy available in the rumen with processed grains vs. more energy available postruminally with unprocessed grains) without affecting the total energy intake. Another factor is that almost all the studies were conducted with dairy cows after the peak of lactation or with relatively low producing cows resulting in cows in positive energy balance.

Rumen Undegradable Protein Supplementation

The use of RUP sources for dairy cows has been extensively reviewed by Santos et al. (1998); however, that review focused on TMR fed in confinement. Supplementation with RUP might be necessary for high producing dairy cows on pasture because the basal diet of pasture has a high ruminal CP degradability (>70%), and therefore provides smaller amounts of RUP compared with cows on TMR diets. The effect of supplementation with isonitrogenous concentrates based on various sources of RDP or RUP on DMI and milk production and composition of high producing dairy cows on pasture is shown in Table 6. All the studies were conducted with cows in early lactation (<75 DIM) supplemented with isonitrogenous concentrates that ranged from 14 to 24% CP, where RDP sources such as soybean meal (Hongerholt and Muller, 1998; McCormick et al., 1999, 2001a, 2001b; Schor and Gagliostro, 2001), sunflower meal (Schroeder and Gagliostro, 2000; Bargo et al., 2001), and urea or rapessed meal (Tesfa et al., 1995) were replaced by RUP sources such as animal protein blend

Table 5. Effect of processing method of corn or sorghum on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹		Pasture ²	Processing type ³	DMI, kg/d			Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d
	DIM	Milk			Supplement	Pasture	Total					
Alvarez et al., 2001	170	NA	ARG/WO	DC corn	5.7	14.8	20.5	17.2	3.13	3.30 ^a	0.57	0.57
				HM corn	6.4	14.6	21.0	17.6	3.29	3.39 ^b	0.57	0.60
Bargo et al., 1998	28	NA ⁴	A/OG	DG corn	5.0	NA	NA	20.2	3.90	3.11	0.79	0.63
				SF corn (290 g/L)	5.0	NA	NA	21.0	3.71	3.10	0.78	0.65
Delahoy et al, 2003	216	33.5	OG	DC corn	7.2	15.5	22.7	24.3	3.73	3.26	0.91	0.79
				SF corn (360 g/L)	7.2	14.6	21.8	24.3	3.58	3.34	0.87	0.81
Pieroni et al., 1999	113	NA	A/OG/WC	DG sorghum (650 g/L)	5.0 + 2.0 (SM pellets) ⁵	12.4 ^a	18.6 ^a	20.2	3.35	3.17	0.68	0.64
				SF sorghum (480 g/L)	5.0 + 2.0 (SM pellets)	14.3 ^b	20.5 ^b	20.8	3.23	3.20	0.67	0.67
Reis and Combs, 2000a	95	NA	A/RC/OG	DG corn (680 g/L)	9.0	10.8	20.0	32.3	3.29	2.94	1.07	0.94
				SR corn (591 g/L)	9.0	10.7	19.8	31.8	3.39	2.98	1.07	0.94
Reis et al., 2001 (Confinement) ⁶	102	NA	A/Q	Control	0.0	17.8 ^a	17.8 ^a	25.6 ^a	3.77 ^a	3.14 ^a	0.98	0.79 ^a
				Finely DG shelled corn	8.9 + 0.5 (SBM) ⁵	11.1 ^b	20.7 ^b	30.7 ^b	3.15 ^b	3.36 ^b	0.96	1.03 ^b
				Coarsely ground HM ear corn	8.5 + 0.7 (SBM)	10.9 ^b	20.3 ^b	29.9 ^b	3.25 ^b	3.35 ^b	0.98	1.02 ^b
Reis et al., 2001 (Confinement) ⁶	167	NA	A/Q	Finely DG shelled corn	9.1 + 0.5 (SBM)	NA	20.6	27.5	3.63	3.52	1.01	0.96
				Coarsely ground HM ear corn	9.1 + 0.7 (SBM)	NA	19.9	25.9	3.69	3.49	0.96	0.90
				Finely ground HM ear corn	9.1 + 0.4 (SBM)	NA	20.0	26.1	3.56	3.61	0.99	0.99
Soriano et al., 2000	107	36.4	OG	HM corn	6.0	NA	NA	30.8	3.13	2.96	1.02	0.89
				Finely DG corn	6.0	NA	NA	29.7	2.94	2.99	0.86	0.87
				Coarsely DG corn	6.0	NA	NA	30.1	3.23	2.96	0.99	0.87
				HM corn	4.0	NA	NA	30.5	3.10	2.95	0.94	0.88
Wu et al., 2001	247	>30	RC/Q	DC shelled corn	6.7 + 1.0 (CS) ⁵ + 0.95 (RS) ⁵	NA	NA	20.5 ^a	3.67 ^a	3.15 ^a	0.76	0.68 ^a
				Finely ground HM corn	6.7 + 1.0 (CS) + 0.95 (RS)	NA	NA	22.9 ^b	3.28 ^b	3.26 ^b	0.75	0.77 ^b

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$; unless otherwise stated; $P < 0.10$ for protein content; Alvarez et al. (2001) and Wu et al. (2001)).

¹Pre-experimental DIM and milk production (kg/d).

²A= alfalfa (*Medicago sativa*); ARG = annual ryegrass (*Lolium multiflorum*); OG = orchardgrass (*Dactylis glomerata*); Q = quackgrass (*Elytrigia repens*); RC = red clover (*Trifolium pratense*); WC = white clover (*Trifolium repens*); WO = winter oats (*Avena sativa*).

³DC = dry cracked, DG = dry ground, HM = high moisture; SF = steam-flaked, between parentheses density; SR = steam-rolled, between parentheses density.

⁴Not available.

⁵CS = corn silage; RS = roasted soybean; SBM = soybean meal; SM = sunflower meal.

⁶In confinement studies, fresh-cut forage was used instead of grazed pasture.

Table 6. Effect of RUP supplementation on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹		Pasture ²	Protein source ³	DMI, kg/d			Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d
	DIM	Milk			Supplement	Pasture	Total					
Bargo et al., 2001	71	20.4	WO	SM (15.3, 39.3) ⁴	6.2	12.1	18.3	19.6	3.78	3.61 ^a	0.74	0.71
				SM (23.3, 35.8)	6.4	14.4	20.8	20.6	3.66	3.43 ^b	0.76	0.70
				FtM (24.6, 46.3)	6.4	13.2	19.7	21.5	3.76	3.35 ^c	0.81	0.72
Hongerholt and Muller, 1998	68	39.8	OG	SBM (14.7, 47.0)	9.3	10.6	19.9	34.2	3.53	2.89	1.20	0.98
				APB (13.7, 62.3)	9.0	11.9	20.9	35.5	3.29	2.87	1.16	1.01
McCormick et al., 1999	42	NA ⁵	ARG	SBM (22.4, 31.7)	10.3 + 1.6 (hay)	10.5 ^a	22.3	32.2	3.35	3.30	1.08	1.07
				SBM (22.4, 31.7)	10.1 + 1.8 (hay) + 7.5 (corn silage)	4.2 ^b	23.5	32.1	3.56	3.29	1.14	1.06
				CGM (22.5, 51.1)	9.2 + 1.9 (hay) + 7.2 (corn silage)	4.2 ^b	22.4	31.7	3.48	3.23	1.10	1.02
McCormick et al., 2001a	44	35.6	ARG	SBM (22.8, 23.2)	10.3 + 1.3 (hay)	12.5	24.1	31.3 ^a	3.34 ^a	3.42 ^a	1.01 ^a	1.03 ^a
				SBM (16.6, 36.7)	9.3 + 1.3 (hay)	12.6	23.2	31.2 ^a	3.11 ^b	3.27 ^c	0.90 ^b	0.94 ^b
				CGM/BM (16.2, 66.7)	10.1 + 1.3 (hay)	13.1	24.5	29.6 ^b	3.27 ^a	3.32 ^b	0.92 ^b	0.94 ^b
McCormick et al., 2001b (Confinement) ⁶	72	42.6	ARG	Solvent SBM (13.5, 43.0)	10.8	12.1 ^a	22.8	39.3	3.24	2.95	1.22	1.10
				Expeller SBM (14.0, 53.6)	11.5	11.3 ^b	22.8	39.9	3.39	3.02	1.34	1.18
Schor and Gagliostro, 2001	5	NA	RG/RC	SBM (20.8, NA)	5.9	13.7 ^a	19.6 ^a	24.9 ^a	3.30	2.78	0.88	0.74
				BM (22.9, NA)	5.7	17.2 ^b	22.9 ^b	29.3 ^b	3.26	2.85	0.90	0.85
Schroeder and Gagliostro, 2000	25	NA	A/RG	SM (19.5, NA)	5.0	NA	NA	25.2 ^a	3.22	3.19	0.82	0.81
				FM (19.7, NA)	5.0	NA	NA	26.8 ^b	3.32	3.28	0.91	0.90
Tesfa et al., 1995	NA	NA	F	Barley/beet pulp (12.4, 23.2)	6.93 + 0.32 (hay)	11.7	NA	27.9	3.99	3.39 ^a	1.11	0.95
				Urea (15.0, 18.6)	6.75 + 0.39 (hay)	10.8	NA	27.9	3.82	3.27 ^b	1.06	0.90
				RM (15.4, 23.6)	7.03 + 0.39 (hay)	10.9	NA	28.2	3.81	3.33 ^a	1.03	0.92
				HT-RM (15.6, 27.6)	6.71 + 0.39 (hay)	11.6	NA	28.1	3.98	3.38 ^a	1.13	0.94

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹Pre-experimental DIM and milk production (kg/d).

²A = alfalfa (*Medicago sativa*); ARG = annual ryegrass (*Lolium multiflorum*); F = fescue (*Festuca pratense*); OG = orchardgrass (*Dactylis glomerata*); RC = red clover (*Trifolium pratense*); RG = perennial ryegrass (*Lolium perenne*); WO = winter oats (*Avena sativa*).

³APB = animal protein blend (meat and bone meal, blood meal, feather meal, poultry by-product meal, and fish meal); BM = blood meal; CGM = corn gluten meal; FM = fish meal; FtM = feather meal; HT-RM = heat treated rapeseed meal; RM = rapeseed meal; SBM = soybean meal; SM = sunflower meal.

⁴Between parentheses %CP and %RUP/CP in the concentrate, respectively.

⁵Not available.

⁶In confinement studies, fresh cut-forage was used instead of grazed pasture.

(Hongerholt and Muller, 1998), corn gluten meal (McCormick et al., 1999; 2001a), expeller soybean meal (McCormick et al., 2001b), blood meal (McCormick et al., 2001a; Schor and Gagliostro, 2001), feather meal (Bargo et al., 2001), heat-treated rapeseed meal (Tesfa et al., 1995), and fish meal (Schroeder and Gagliostro, 2000).

Pasture DMI was not affected by replacing RDP sources with RUP sources in five of seven studies (Tesfa et al., 1995; Hongerholt and Muller, 1998; McCormick et al., 1999, 2001a; Bargo et al., 2001). McCormick et al. (2001b) reported a 0.8 kg/d lower pasture DMI with cows fed annual ryegrass in confinement when supplemented with a high RUP concentrate. In contrast, Schor and Gagliostro (2001) found that replacing RDP by RUP sources in the concentrate resulted in higher DMI for cows grazing a perennial ryegrass/red clover pasture.

Of the eight studies, only two (Schroeder and Gagliostro, 2000; Schor and Gagliostro, 2001) reported an increase in milk production with supplementation of high RUP concentrates. Milk response ranged from 6 (Schroeder and Gagliostro, 2000) to 18% (Schor and Gagliostro, 2001). Most of the studies reported that the content of RUP in the concentrate supplemented did not affect fat or protein percentage in milk. Milk fat percentage was increased when soybean meal was replaced by corn gluten meal and blood meal (McCormick et al., 2001a). Two studies showed inconsistent results in milk protein percentage, with reductions (Bargo et al., 2001) or increases (McCormick et al., 2001) as the amount of RUP increased, which could be attributed to differences in amino acids composition in the RUP sources.

The amount of RUP escaping the rumen in cows fed pasture-based diets is a function of pasture DMI and its RUP content, and the supplement DMI and its RUP content. The pasture species have a large impact on the amount of RUP. For example, a winter oats pasture containing 18.4% CP and 19.3% RUP (% of CP) provided 472 g/d when constituting 67% of the total diet DMI (Bargo et al., 2001), while an orchardgrass pasture containing 24.8 and 39.1% RUP (% of CP) provided 1096 g/d when constituting 55% of the total diet DMI (Hongerholt and Muller, 1998). Total diet RUP intake was increased from 893 to 1153 g/d (Bargo et al., 2001), from 1077 to 1234 g/d (Hongerholt and Muller, 1998), from 1316 to 1680 g/d (McCormick et al., 1999), from 1109 to 1593 (McCormick et al., 2001a), from 1710 to 1869 g/d (McCormick et al., 2001b), and from 1011 to 1647 g/d (Schor and Gagliostro, 2000). Although, many of the studies did not report a response in milk production when RUP was increased in the concentrate, a significant positive relationship was found between MY (kg/d) and RUP intake (**RUPI**, g/d): $MY = 19.35$ (SE 4.14)

+ 0.0079 (SE 0.0025) **RUPI** ($R^2 = 0.98$). The mean increase in milk production was 0.8 kg/d for each 100 g/d of RUP but widely variable responses and potential cost differences in rations may limit applicability.

Forage Supplementation

Corn silage supplementation. The summary of corn silage supplementation on animal performance of high producing cows on pasture is shown in Table 7. In one of the studies (Stockdale, 1994), cows were supplemented only with corn silage; while in the other studies, cows were supplemented with corn silage plus low (3.2 kg/d; Valk, 1994) or high (8.7 kg/d; Holden et al., 1995) amounts of concentrates. Two of those studies were grazing studies (Stockdale, 1994; Holden et al., 1995), and one study was in confinement (Valk, 1994). Response to corn silage supplementation depends on the amount of pasture offered, which determines the SR and total DMI (Phillips, 1988). Corn silage supplementation had positive effects on production when the amount of pasture offered was low (Stockdale, 1994). When PA was high, the supplementation with 2.3 kg DM/d of corn silage reduced pasture DMI and resulted in a similar total DMI and similar milk production (Holden et al., 1995). Valk (1994) conducted two experiments in confinement with high producing dairy cows fed fresh-cut forage and supplemented with corn silage at different times of the day or mixed with the pasture. Corn silage fed at night did not increase total DMI nor milk production compared with diets containing only fresh-cut forage (Valk, 1994). However, when corn silage was mixed with the fresh-cut forage, both total DMI and milk production increased (Valk, 1994).

Corn silage supplementation did not affect milk fat percentage (Stockdale, 1994; Valk, 1994; Holden et al., 1995). Holden et al. (1995) reported similar milk protein percentage when corn silage supplementation did not increase total DMI. However, Stockdale (1994) reported higher milk protein percentage when supplementation with 6.5 kg DM/d of corn silage increased total DMI. The supplementation of corn silage at night resulted in lower milk protein percentage than the unsupplemented treatment and than feeding the corn silage mixed with the fresh-cut forage (Valk, 1994).

Accounting for the study random effect (St-Pierre, 2001), a negative relationship was found between MPi (kg/d) and SR (kg pasture/kg corn silage) from the data presented in Table 7: $MPi = 4.82$ (SE 0.58) - 4.37 (SE 0.83) SR ($R^2 = 0.87$). As reviewed above, corn silage supplementation may improve milk production of high producing dairy cows depending on the PA. In an extensive review, Phillips (1988) concluded that corn silage supplementation may increase milk production if pas-

Table 7. Effect of forage supplementation on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹		Pasture ²	DMI, kg/d				Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d	Comments
	DIM	Milk		Forage	Concentrate	Pasture	Total						
Corn silage (CS)													
Holden et al., 1995	135	32.0	OG	0.0	8.5	14.2	22.7	29.1	3.61	3.12	1.04	0.90	High PA ³
				2.3	8.8	11.5	22.5	28.8	3.65	3.09	1.05	0.89	CS after each milking
Stockdale, 1994	60	28.0	PC	0.0	...	14.5	14.5	22.1 ^a	3.95	2.52 ^a	0.87	0.56	Low PA ³
				3.8	...	14.5	18.3	26.7 ^b	3.90	2.67 ^{ab}	1.04	0.71	
				6.5	...	14.0	20.5	26.4 ^b	3.92	2.72 ^b	1.03	0.72	
				8.3	...	12.8	21.1	26.3 ^b	3.74	2.67 ^{ab}	0.98	0.70	
Valk, 1994 ⁴	53	37.1	RG	0.0	3.2	13.1	16.3 ^a	27.0 ^a	4.53	3.14 ^a	1.22 ^a	0.85 ^a	Control
(Confinement) ⁵				7.3 ^a	3.1	6.4	16.8 ^a	26.6 ^a	4.62	2.98 ^b	1.23 ^a	0.79 ^a	CS fed at night
				8.1 ^b	3.2	6.7	18.0 ^b	29.7 ^b	4.68	3.11 ^a	1.39 ^b	0.92 ^b	CS mixed with pasture
Valk, 1994 ⁴	90	34.2	RG	7.9	3.2	6.9	18.0	28.0	4.58	3.18	1.28	0.89	CS mixed with pasture
(Confinement) ⁵				4.6	3.2	10.1	17.9	27.4	4.52	3.25	1.24	0.89	CS after each milking
Hay													
Rearte et al., 1986a	88	NA ³	OG	0.0	8.4	NA	NA	27.2 ^a	3.34 ^a	3.13	0.91	0.85	
				1.1 (chopped)	8.4	NA	NA	27.9 ^{ab}	3.32 ^{ab}	3.14	0.89	0.88	
				0.9 (long)	8.4	NA	NA	28.3 ^b	3.20 ^b	3.13	0.91	0.89	
Rearte et al., 1986b	74	36.5	OG	0.0	8.7	16.6	25.3	36.8	3.40	3.05	1.25	1.12	
				2.7 (A ²)	9.2	15.8	27.7	37.1	3.36	3.03	1.25	1.12	
Reis and Combs, 2000a	95	NA	A/RC/OG	0.0	9 (dry corn)	10.8 ^a	20.0	32.3	3.29	2.94	1.07	0.94	
				3.2 (long A ²)	9 (dry corn)	8.2 ^b	20.3	31.5	3.32	2.96	1.04	0.92	
				0.0	9 (steam-rolled corn)	10.7 ^a	19.8	31.8	3.39	2.98	1.07	0.94	
				3.2 (long A ²)	9 (steam-rolled corn)	7.6 ^b	19.7	32.7	3.38	2.99	1.10	0.97	
Stockdale, 1999b	105 to 222	30 to 16.9	RG/WC/P	0.0	...	14.0 ^a	14.0 ^a	18.2 ^a	4.26	3.16	0.78	0.59	
				3.9	...	12.7 ^b	16.6 ^b	20.1 ^b	4.27	3.13	0.86	0.63	
Wales et al., 2001	49	25.2	RG/WC	0.0	...	15.6 ^a	15.6 ^b	24.2 ^{ab}	3.68	3.00	0.89	0.73	
				2.4 ^c (pellet)	...	10.9 ^{bc}	13.3 ^c	22.1 ^{bc}	3.75	2.81	0.83	0.62	
				2.1 ^c (cube)	...	10.6 ^{bcd}	12.7 ^c	20.1 ^c	3.75	2.84	0.75	0.57	
				4.5 ^b	Barley-based	10.3 ^{cd}	14.8 ^b	26.2 ^a	3.57	3.03	0.94	0.79	
				7.2 ^a (pellet)	Barley-based	10.1 ^{cd}	17.3 ^a	25.6 ^a	3.73	3.08	0.95	0.79	
				7.4 ^a (cube)	Barley-based	10.0 ^d	17.4 ^a	25.7 ^a	3.43	2.88	0.88	0.74	

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹Pre-experimental DIM and milk production (kg/d).

²A = alfalfa (*Medicago sativa*); OG = orchardgrass (*Dactylis glomerata*), P = paspalum (*Paspalum dilatatum*); PC = Persian clover; RC = red clover (*Trifolium pratense*); RG = perennial ryegrass (*Lolium perenne*); WC = white clover (*Trifolium repens*).

³PA = pasture allowance.

⁴OM intake.

⁵In confinement studies, fresh cut-forage was used instead of grazed pasture.

ture offered is restricted (i.e., low PA, low SR) but if pasture is offered ad libitum (i.e., high PA, high SR) milk production does not change or could decrease.

Hay supplementation. Studies on hay supplementation to high producing dairy cows on pasture are shown in Table 7. Four of those were conducted with cows in early lactation supplemented also with high (>8 kg DM/d; Rearte et al., 1986a, 1986b; Reis and Combs, 2000) or low (<8 kg DM/d, Wales et al., 2001) amounts of concentrate, and only one (Stockdale, 1999b) with cows receiving hay as the only supplement. Hay was supplemented in different forms including long hay (Rearte et al., 1986a; Reis and Combs, 2000a), chopped hay added to the concentrate (Rearte et al., 1986a), or pellets and cubes of hay (Wales et al., 2001). Amount of hay supplemented varied from 0.9 (Rearte et al., 1986a) to 3.9 kg DM/d (Stockdale, 1999b).

Different forms and amounts of hay supplementation reduced pasture DMI, with an overall reduction averaging 3.5 kg/d (range: 0.8 to 5.6 kg/d). The effect on total DMI depended on the SR. In the study of Reis and Combs (2000a), hay supplementation resulted in a SR from 0.81 to 0.97 kg pasture/kg hay, which resulted in similar total DMI. In contrast, in the study of Stockdale (1999b), hay supplementation determined a SR of 0.33 kg pasture/kg hay and increased total DMI. Rearte et al. (1986b) reported no effect of hay supplementation on pasture or total DMI. Hay supplemented in a pellet or a cube form, either alone or added to the concentrate, decreased pasture DMI compared with a pasture-only diet treatment (Wales et al., 2001).

Three studies with early lactation cows (Rearte et al., 1986b; Reis and Combs, 2000a; Wales et al., 2001) reported no response in milk production to hay supplementation, while one (Rearte et al., 1986a) found higher milk production when long hay was supplemented, but similar milk production when the hay was chopped and added to the concentrate. Stockdale (1999b) also reported higher milk production when cows were supplemented with hay compared with cows fed pasture-only diets. Most of the studies (Rearte et al., 1986b; Stockdale, 1999b; Reis and Combs, 2000a; Wales et al., 2001) found no effect of hay supplementation on milk fat percentage, except for Rearte et al. (1986a), who reported lower milk fat content with long hay supplementation. None of the studies (Rearte et al., 1986a, 1986b; Stockdale, 1999b; Reis and Combs, 2000a; Wales et al., 2001) reported changes in milk protein percentage with hay supplementation.

Hay supplementation to grazing dairy cows raises the question about the fiber requirements of high producing dairy cows on pasture. Recent recommendations by NRC (2001) for dairy cows suggested a minimum of 25% NDF and 19% NDF from forages for the following

specific conditions: forage with adequate particle size, dry corn as the predominant starch source, and diets fed as TMR. When concentrates are fed twice daily and separately from forage, NDF minimum requirements are unknown but probably higher than 25% (NRC, 2001). The NRC (2001) concluded that because of lack of data, specific recommendations for NDF for grazing dairy cows are not known. In agreement with that, the number of studies presented in Table 7 is not large enough to make specific recommendation for NDF requirements for grazing dairy cows. Total diet NDF content in those studies varied from 24.6 to 51.1%. In the study of Reis and Combs (2000a), the total diet NDF content averaged 24.8%, which is similar to the minimum recommendations of NRC (2001) without affecting milk fat percentage. Supplementation with 3.2 kg DM/d of long alfalfa hay did not increase NDF intake because of the high SR (0.89 kg pasture/kg hay) and the similar NDF content between the pasture (35.8%) and the hay (36.1%; Reis and Combs, 2000a). Supplementation with 2.3 kg DM/d of hay as a pellet or as a cube did not affect either the total NDF intake or the milk fat content (Wales et al., 2001). None of the studies reviewed reported information on the content of effective fiber in the diets. Using the CNCPS ruminal pH equation and a database from 23 pasture studies, Kolver and deVeth (2002) estimated that the effective fiber was 29% when ruminal pH was between 5.8 and 6.0 and 78% when ruminal pH was between 6.6 and 6.8, with an overall average of 43%. More information in minimum requirements of NDF and effective fiber is needed for high producing dairy cows on pasture supplemented twice daily.

Fat Supplementation

Research on the effect of fat supplementation on DMI and milk production and composition of high producing dairy cows on pasture is presented in Table 8. Some of the studies supplemented cows with concentrates with fat sources that partially replaced some of the concentrate ingredients (Garnsworthy, 1990; Gallardo et al., 2001) or were added to a basal amount of concentrate (King et al., 1990; Agenäs et al., 2002; Schroeder et al., 2002). Sources of fat included ruminally inert sources such as hydrogenated fish fat (Gallardo et al., 2001), Ca-salts of long-chain fatty acids (Garnsworthy, 1990), high melting point fatty acids (King et al., 1990; Schroeder et al., 2002); or nonruminally inert sources such as full fat rapeseed (Murphy et al., 1995), and soybean oil (Agenäs et al., 2002). The amount of fat supplemented ranged from 200 (Gallardo et al., 2001) to 1000 g/d (Schroeder et al., 2002).

Table 8. Effect of fat supplementation on DMI and milk production and composition of dairy cows on pasture.

Reference	Cow ¹			Concentrate type ³	DMI, kg/d			Milk kg/d	Fat %	Protein %	Fat kg/d	Protein kg/d
	DIM	Milk	Pasture ²		Supplement	Pasture	Total					
Agenäs et al., 2002	194	35.1	MF	Concentrate	6.7 + 0.7	NA ⁴	NA	24.2	4.53 ^a	3.51	1.09	0.84
				Concentrate + 7% soybean oil	6.3 + 0.8	NA	NA	26.9	3.58 ^b	3.39	1.03	0.90
Gallardo et al., 2001	132	NA	A	Corn/sorghum/soybean concentrate (C)	3.7	11.4	15.1	23.9 ^a	3.54	2.99	0.85 ^a	0.72 ^a
				C including fat (hydrogenated fish fat)	3.3	11.9	15.2	26.4 ^b	3.56	3.01	0.94 ^b	0.79 ^b
Garnsworthy, 1990	NA	NA	Perennial grass	Starch (barley)	4.0	NA	NA	21.2	3.71 ^a	3.30	0.79 ^a	0.68
				Fiber (oatfeed) + protected fat (Ca salts)	4.0	NA	NA	20.7	4.26 ^b	3.20	0.88 ^b	0.65
Garnsworthy, 1990	NA	NA	Perennial grass	Starch (barley/corn)	4.0	NA	NA	21.3	3.99 ^a	3.44 ^{ab}	0.86 ^a	0.73
				Starch + protected fat (Ca salts)	4.0	NA	NA	22.5	4.45 ^{bc}	3.42 ^{ab}	0.99 ^b	0.77
				Fiber (oatfeed)	4.0	NA	NA	22.9	4.27 ^{ab}	3.48 ^a	0.98 ^{ab}	0.80
				Fiber + protected fat (Ca salts)	4.0	NA	NA	22.3	4.71 ^c	3.30 ^b	1.06 ^b	0.73
King et al., 1990	35	22.8	RG/WC	Control	0.0	17.0	17.0 ^a	23.4 ^a	4.32 ^{ab}	2.88	1.01 ^a	0.67 ^a
				Barley	3.3	16.3	19.6 ^b	25.3 ^{ab}	4.02 ^a	3.03	1.00 ^a	0.75 ^b
				Barley + fat (15% of concentrate)	3.8	15.6	19.4 ^b	26.0 ^b	4.36 ^b	2.99	1.03 ^b	0.77 ^b
Murphy et al., 1995	21	NA	NA	Control	0.0	NA	NA	21.2 ^a	3.61 ^a	3.27	0.76	0.69
				Full fat rapeseed	3.0	NA	NA	22.8 ^b	3.19 ^b	3.20	0.73	0.72
Schroeder et al., 2002	-19	NA	A/OG	Corn/fish meal concentrate (C)	5.2 ^a	17.8 ^a	23.0	25.6	3.44 ^a	3.24	0.87 ^a	0.83
				C + 0.5 kg/d fat (hydrogenated oil)	5.5 ^{ab}	14.3 ^{ab}	19.8	26.9	3.51 ^a	3.32	0.93 ^{ab}	0.87
				C + 1 kg/d fat (hydrogenated oil)	6.0 ^b	13.6 ^b	19.6	27.2	3.78 ^b	3.18	1.03 ^b	0.86

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹Pre-experimental DIM and milk production (kg/d).

²A = alfalfa (*Medicago sativa*); MF = meadow fescue (*Poa pratensis*); OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*); WC = white clover (*Trifolium repens*).

³Main energy and protein sources in the concentrate.

⁴Not available.

Only three studies (Gallardo et al., 2001; King et al., 1990; Schroeder et al., 2002) measured pasture DMI. Two of the studies reported no differences in DMI when fat partially replaced concentrate ingredients (Gallardo et al., 2001) or was added to the basal amount of concentrate (King et al., 1990). Schroeder et al. (2002) reported a linear reduction in pasture DMI as the amount of fat added to the basal concentrate increased from 0 to 1 kg/d. The large amount of fat supplementation may have affected physiological mechanisms of intake regulation (Schroeder et al., 2002). Total DMI was not affected by fat supplementation in any of the studies because fat supplement either did not reduce pasture DMI when partially replaced concentrate ingredients (Gallardo et al., 2001), or reduced pasture DMI when added over a basal amount of concentrate (King et al., 1990; Schroeder et al., 2002).

The effect of fat supplementation on milk production is not consistent, with some studies showing no effect (Garnsworthy, 1990; King et al., 1990; Agenäs et al., 2002) and some studies showing positive effect (Murphy et al., 1995; Gallardo et al., 2001; Schroeder et al., 2002). The addition of a ruminally inert fat source (Ca-salts of long chain fatty acids) to starch or fiber-based concentrates did not improve milk production (Garnsworthy, 1990). Likewise, no milk production response was found when a fat source of high melting point was added as 15% (as fed) of a basal amount of barley concentrate (King et al., 1990). Agenäs et al. (2002) reported no effect of adding soybean oil to the diet of grazing cows supplemented with 6.5 kg DM/d of concentrate and 0.8 kg DM/d of hay. Milk production was increased by partially replacing corn by hydrogenated fish fat in a concentrate supplemented at a rate lower than 4 kg DM/d (Gallardo et al., 2001). Compared with cows fed pasture-only diets, supplementation with 3 kg DM/d of full fat rapeseed increased milk production (Murphy et al., 1995). Schroeder et al. (2002) reported higher FCM when 1 kg/d of fat plus 5.2 kg DM/d of a corn-based concentrate were supplemented.

Four of the six studies (Garnsworthy, 1990; King et al., 1990; Schroeder et al., 2002) reported that milk fat percent increased with saturated fat supplements. In two experiments by Garnsworthy (1990), the inclusion of ruminally inert fat in starch or fiber-based concentrates increased milk fat content. The highest fat percentage was obtained with the fiber-based concentrate with fat, suggesting that fiber and ruminally inert fat may have an additive effect (Garnsworthy, 1990). Milk fat percentage was higher when 0.5 kg/d of fat was added to 3.3 kg DM/d of barley (King et al., 1990). Schroeder et al. (2002) also reported an increase in milk fat content with 1 kg/d of fat compared with a basal concentrate without fat or 0.5 kg/d of fat. Overall, milk

fat percentage increased 0.43 percentage units (range: 0.34 to 0.55 percentage units) or 13% (range: 10 to 17%) in those studies. Gallardo et al. (2001) reported no changes in milk fat content with fat supplementation. Supplementation with fat sources rich in unsaturated fatty acids such as soybean oil (Agenäs et al., 2002) or full-fat rapeseed (Murphy et al., 1995), however, resulted in reductions of milk fat content. Most of the studies (Garnsworthy, 1990; King et al., 1990; Murphy et al., 1995; Gallardo et al., 2001; Agenäs et al., 2002; Schroeder et al., 2002) reported no changes in milk protein percentage with fat supplementation. In only one of the two experiments of Garnsworthy (1990), milk protein content was reduced when ruminally inert fat was added to a fiber-based concentrate.

Overall, fat supplementation did not affect total DMI (−0.3 kg/d, SE 1.3 kg/d, range: −0.8 to 10.6 kg/d; Student's *t*-test, significantly different from zero, $P = 0.83$), increased milk production 1.43 kg/d (SE 0.37 kg/d, range: −0.60 to 2.70 kg/d; Student's *t*-test, significantly different from zero, $P < 0.01$) or 6%, increased fat yield 0.063 kg/d (SE 0.023 kg/d, range: −0.06 to 0.16 kg/d; Student's *t*-test, significantly different from zero, $P < 0.02$), and increased protein yield 0.035 kg/d (SE 0.035 kg/d, range: −0.07 to 0.10 kg/d; Student's *t*-test, significantly different from zero, $P < 0.05$) compared with the no-fat treatments. Neither fat (0.025 percentage units, SE 0.149 percentage units, range: −0.95 to 0.55 percentage units; Student's *t*-test, significantly different from zero, $P = 0.87$) nor protein (−0.019 percentage units, SE 0.034 percentage units, range: −0.18 to 0.15 percentage units; Student's *t*-test, significantly different from zero, $P = 0.59$) percentages were affected by fat supplementation. However, caution should be used in this conclusion because of the low number of studies with cows producing less than 30 kg/d.

RUMINAL DIGESTION AND FERMENTATION ON GRAZING COWS

Ruminal Fermentation on Pasture-Only Diets

Ruminal fermentation on pasture-only diets has been reported for dairy cows consuming the same forage as grazed pasture, hay, or silage (Holden et al., 1994); fresh-cut forage harvested at different seasons (Elizalde et al., 1994; 1996); and pasture fertilized with different amounts of N (Van Vuuren et al., 1992; Mackle et al., 1996; Peyraud et al., 1997) (Table 9). Ruminal $\text{NH}_3\text{-N}$ concentration and total VFA concentration were higher in cows grazing an orchardgrass pasture than in cows consuming orchardgrass as hay or silage (Holden et al., 1994). Dairy cows fed fresh-cut winter oats had highest ruminal pH in fall and late spring, and lowest ruminal

Table 9. Effect of maturity, forage form, and N fertilization on ruminal fermentation of dairy cows on pasture.

Reference	Pasture			Treatment	pH	NH ₃ -N mg/dl	VFA, mmol/L			
	Species ¹	CP, %	NDF, %				Total	Acetate ²	Propionate ²	Butyrate ²
Elizalde et al., 1994; 1996 (Confinement) ⁴	WO	23.3	46.4	Autumn	6.64 ^a	32.6 ^a	NA ³	NA (76.3 ^a)	NA (17.1 ^b)	NA (6.62 ^{ab})
		21.1	47.5	Early winter	6.34 ^b	15.0 ^b	NA	NA (70.8 ^{ab})	NA (20.6 ^a)	NA (8.6 ^{ab})
		21.7	46.6	Late winter	6.03 ^c	19.5 ^b	NA	NA (74.6 ^{ab})	NA (17.5 ^{ab})	NA (7.8 ^{ab})
		11.7	43.4	Early spring	6.02 ^c	5.1 ^c	NA	NA (67.2 ^b)	NA (20.4 ^a)	NA (12.5 ^a)
		10.3	57.1	Late spring	6.37 ^{ab}	5.1 ^c	NA	NA (74.2 ^{ab})	NA (20.2 ^{ab})	NA (5.6 ^b)
Holden et al., 1994	OG	17.1	49.4	Pasture	NA	13.7 ^a	131.7 ^a	NA (71.0)	NA (17.1)	NA (8.9 ^a)
		17.4	63.5	Hay	NA	10.9 ^b	118.4 ^b	NA (73.2)	NA (18.0)	NA (6.4 ^b)
		16.9	55.9	Silage	NA	11.0 ^b	118.4 ^b	NA (71.3)	NA (18.8)	NA (7.2 ^c)
Mackle et al., 1996 (Confinement) ⁴	RG/WC	22.1	46.3	25 kg N/ha – ad libitum	6.06 ^c	34.5	NA	NA	NA	NA
		22.1	46.3	25 kg N/ha – restricted	6.31 ^d	35.9	NA	NA	NA	NA
		23.0	47.3	125 kg N/ha – ad libitum	6.19 ^a	36.6	NA	NA	NA	NA
		23.0	47.3	125 kg N/ha – restricted	6.38 ^b	38.9	NA	NA	NA	NA
Peyraud et al., 1997 (Confinement) ⁴	RG	10.6	52.8	0 kg N/ha	6.2	1.5 ^b	103.0 ^b	NA (61.9 ^b)	NA (21.1)	NA (14.5 ^b)
		15.0	49.6	80 kg N/ha	6.2	9.9 ^a	117.0 ^a	NA (64.7 ^a)	NA (20.2)	NA (11.9 ^a)
Van Vuuren et al., 1992 (Confinement) ⁴	RG			June-July						
		17.4	39.8	275 kg N/ha	6.10 ^a	15.9 ^a	119.0	NA	NA	NA
		21.2	37.3	500 kg N/ha	6.60 ^b	25.5 ^b	125.0	NA	NA	NA
				September-October						
		16.8	40.9	275 kg N/ha	6.20	18.5 ^a	118.0 ^a	NA	NA	NA
		19.6	33.1	500 kg N/ha	6.10	28.9 ^b	140.0 ^b	NA	NA	NA

^{a,b,c}Means within reference with different superscripts differ ($P < 0.05$).

¹OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*); WO = winter oats (*Avena sativa*); WC = white clover (*Trifolium repens*).

²Between parentheses individual VFA expressed as molar proportion (mol/100 mol).

³Not available.

⁴In confinement studies, fresh cut-forage was used instead of grazed pasture.

pH in late winter and early spring (Elizalde et al., 1994; 1996). Ruminal $\text{NH}_3\text{-N}$ concentration were highest in fall and lowest in early and late spring, which was associated with a decrease in the CP content of pasture from 23.3 to 10.3% (Elizalde et al., 1994; 1996).

Three studies focused on the effect of N fertilization on ruminal fermentation of dairy cows fed ryegrass (Van Vuuren et al., 1992; Mackle et al., 1996; Peyraud et al., 1997). Ruminal pH was increased in dairy cows fed ryegrass when N fertilization was increased from 275 to 500 kg N/ha (Van Vuuren et al., 1992) or from 25 to 125 kg N/ha (Mackle et al., 1996). Peyraud et al. (1997), however, found no differences in ruminal pH between cows fed unfertilized or fertilized (80 kg N/ha) ryegrass. Nitrogen fertilization increased ruminal $\text{NH}_3\text{-N}$ concentration in two studies (Van Vuuren et al., 1992; Peyraud et al., 1997) but did not in a third study (Mackle et al., 1996). Contradictory results could be explained because N fertilization increased pasture CP and CP intake in the studies of Peyraud et al. (1997) and Van Vuuren et al. (1992) but not in the study of Mackle et al. (1996).

Effect of Supplementation on Ruminal Fermentation

Level of concentrate supplementation. Studies that have reported ruminal fermentation data of dairy cows on pasture supplemented with different amounts of energy supplements are summarized in Table 10. Supplementation amounts ranged from 0 to 10 kg DM/cow per day including corn-based concentrates (Berzaghi et al., 1996; Jones-Endsley et al., 1997; Bargo et al., 2002a), corn flour and dextrose monohydrate (Carruthers and Neil, 1997; Carruthers et al., 1997), grains as barley or corn (García et al., 2000; Reis and Combs, 2000b), or concentrates based on starch and fiber sources (Van Vuuren et al., 1986; Sayers, 1999; Khalili and Sairanen, 2000).

Ruminal pH was reduced by large amounts of concentrate supplementation (>8 kg DM/d) in cows grazing orchardgrass (Bargo et al., 2002a), but also by low amounts (<1.5 kg DM/d) of a NSC supplement (50:50 corn flour and dextrose monohydrate) in cows fed in confinement with ryegrass (Carruthers and Neil, 1997; Carruthers et al., 1997). However, other studies reported similar ruminal pH between pasture-only diets and pasture plus 5.4 kg DM/d of cracked corn (Berzaghi et al., 1996), 2.5 kg DM/d of barley or corn (García et al., 2000), 4 kg DM/d of barley or barley/oats/beet pulp (Khalili and Sairanen, 2000), 5 or 10 kg DM/d of a corn (Reis and Combs, 2000b), or 5.3 kg DM/d of a high-starch or low-starch based concentrate (Van Vuuren et al., 1986). Increasing the amount of concentrate from 5

to 10 kg DM/d reduced ruminal pH in one study (Sayers, 1999) but increasing the amount of concentrate from 5.6 to 8.4 kg DM/d did not affect ruminal pH in another study (Jones-Endsley et al., 1997).

The lack of consistency with the amount of concentrate supplementation on ruminal pH of dairy cows on pasture suggests that there is not a simple relationship between amount of concentrate supplemented and ruminal pH. Kolver and deVeth (2002) concluded that no single dietary variable or group of variables could be used to reliably predict ruminal pH. The interaction between the amount and type of concentrate supplemented and pasture DMI and quality (e.g., stage of maturity, NDF content) may have a key role. However, when dividing the studies into those using high (<50% NDF; Carruthers and Neil, 1997; Carruthers et al., 1997; García et al., 2000; Jones-Endsley et al., 1997; Reis and Combs, 2000b; Van Vuuren et al., 1986) or medium (>50% NDF; Berzaghi et al., 1996; Sayers, 1999; Khalili and Sairanen, 2000; Bargo et al., 2002a) quality pastures, no consistent pattern was found. The timing of rumen sample collection in relation to feeding could be also affecting these results. The studies reviewed measured ruminal pH 6 times every 4 h for a 24-h period (García et al., 2000; Bargo et al., 2002a) or from 2000 to 1600 h (Van Vuuren et al., 1986); 1 time at 0500 h (Berzaghi et al., 1996); 4 times at 0800, 1200, 1600, and 2000 h (Carruthers and Neil, 1997; Carruthers et al., 1997); 4 times at 2, 4, 6, and 8 h after feeding (Jones-Endsley et al., 1997); eight times every 1.5 to 3 h from 0700 to 2200 h (Khalili and Sairanen, 2000); or every 2 to 3 h from 0500 to 2100 h (Sayers, 1999); and 10 times every 1 to 3 h starting before the morning concentrate feeding (Reis and Combs, 2000b).

Reductions in ruminal pH with supplementation were associated with higher total VFA concentrations in some studies (Sayers, 1999; Bargo et al., 2002a). However, most of the studies reported no effect of supplementation on total VFA concentration (Van Vuuren et al., 1986; Berzaghi et al., 1996; Jones-Endsley et al., 1997; Sayers, 1999; García et al., 2000; Khalili and Sairanen, 2000; Reis and Combs, 2000b), even with reductions in ruminal pH (Carruthers and Neil, 1997; Carruthers et al., 1997). Kolver and deVeth (2002) reported a negative relationship between ruminal pH and total VFA concentration based on 86 treatments from a database from 23 pasture-based studies, but the R^2 value was 0.30. Concentrate supplements reduced molar proportion of acetate and increased the molar proportion of propionate in some studies (Sayers, 1999; García et al., 2000; Bargo et al., 2002a). Some of the studies reported only a reduction in the acetate molar proportion (Khalili and Sairanen, 2000) or an increase

Table 10. Effect of amount of energy supplementation on ruminal fermentation of dairy cows on pasture.

Reference	Pasture ¹	Concentrate		pH	NH ₃ -N mg/dl	VFA, mmol/L			
		Type	DMI, ² kg/d			Total	Acetate ³	Propionate ³	Butyrate ³
Bargo et al., 2002a	OG low PA	Mineral-vitamin mix	0.8 (5%)	6.57 ^a	15.2 ^a	116.3 ^a	79.3 ^a (68.2 ^a)	22.3 ^a (19.1 ^a)	10.7 ^a (9.2 ^a)
		Corn based	8.6 (35%)	6.25 ^c	9.1 ^b	130.0 ^b	85.1 ^a (65.8 ^b)	25.6 ^b (19.5 ^b)	14.8 ^b (11.3 ^b)
	OG high PA	Mineral-vitamin mix	0.7 (4%)	6.40 ^b	15.3 ^a	129.8 ^b	88.9 ^b (68.6 ^a)	24.1 ^a (18.5 ^a)	12.5 ^c (9.6 ^a)
		Corn based	8.7 (35%)	6.29 ^c	8.7 ^b	130.6 ^b	84.9 ^b (65.2 ^b)	26.2 ^a (19.9 ^b)	15.1 ^d (11.6 ^b)
Berzaghi et al., 1996	TF/OG/WC	Control	0.0	6.4	22.4	150.0	NA ⁴ (63.2)	NA (18.7)	NA (12.9)
		Cracked corn	5.4 (36%)	6.2	17.1	148.0	NA (62.4)	NA (19.1)	NA (13.5)
Carruthers and Neil, 1997 (Confinement) ⁵	RG high N	Control	0.0	6.19 ^a	29.9 ^a	132.0 ^a	50.4 (NA)	24.3 (NA)	17.3 (NA)
		NSC supplement	1.3 (8%)	6.05 ^c	22.4 ^b	136.0 ^a	51.7 (NA)	25.5 (NA)	15.0 (NA)
	RG low N	Control	0.0	6.17 ^a	12.8 ^c	125.0 ^b	52.0 (NA)	25.3 (NA)	15.9 (NA)
		NSC supplement	1.3 (8%)	6.11 ^b	9.2 ^d	126.0 ^b	52.0 (NA)	24.1 (NA)	18.5 (NA)
Carruthers et al., 1997 (Confinement) ⁵	RG	Control	0.0	6.08 ^a	39.1 ^a	149.4	65.1 (NA)	18.4 (NA)	12.5 (NA)
		NSC supplement	1.1 (7%)	6.00 ^b	32.3 ^b	151.4	64.7 (NA)	19.2 (NA)	12.1 (NA)
García et al., 2000 (Confinement) ⁵	WO	Control	0.0	6.10	29.0 ^a	96.7	NA (61.5 ^a)	NA (19.6 ^a)	NA (13.7 ^{ab})
		Barley (24% starch diet)	2.6 (35%)	6.09	19.4 ^c	90.3	NA (57.8 ^b)	NA (24.9 ^b)	NA (11.9 ^a)
		Corn (24% starch diet)	2.4 (29%)	6.02	26.9 ^b	97.3	NA (60.1 ^b)	NA (21.4 ^c)	NA (13.7 ^b)
Jones-Endsley et al., 1997	A/OG	Corn based	5.6 (31%)	5.90	19.1	102.8	NA (63.5)	NA (21.2 ^a)	NA (11.9)
			8.4 (42%)	5.82	17.6	102.1	NA (62.9)	NA (22.0 ^b)	NA (11.8)
Khalili and Sairanen, 2000	MF/T	Control	0.0	6.13	28.7 ^{ab}	127.0	NA (65.9 ^a)	NA (19.0)	NA (11.1)
		Barley	4.0 (NA)	6.17	32.1 ^a	127.0	NA (64.1 ^b)	NA (19.1)	NA (12.5)
		Barley/oats/beet pulp	4.0 (NA)	6.01	21.8 ^b	132.0	NA (64.0 ^b)	NA (20.5)	NA (11.6)
Reis and Combs, 2000b	A/RC/RG	Corn	0.0	6.63	22.4 ^a	98.7	65.7 (NA)	17.8 ^a (NA)	9.9 (NA)
			5.0 (28%)	6.72	17.7 ^b	99.0	63.1 (NA)	19.9 ^b (NA)	10.9 (NA)
			10.0 (51%)	6.69	8.1 ^c	104.0	64.2 (NA)	23.9 ^c (NA)	11.3 (NA)
Sayers, 1999	RG	Concentrate	5.0 (28%)	6.00 ^a	13.9	119.3	NA (60.1 ^a)	NA (21.5 ^a)	NA (14.8)
			10.0 (50%)	5.75 ^b	11.7	124.8	NA (56.3 ^b)	NA (25.3 ^b)	NA (14.2)
Van Vuuren et al., 1986	RG	High starch	0.8 (6%)	6.0	32.3 ^a	127.0	NA	NA	NA
		High starch	5.4 (32%)	5.9	22.1 ^b	127.0	NA	NA	NA
		Low starch	5.2 (29%)	5.9	20.4 ^b	130.0	NA	NA	NA

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹A = alfalfa (*Medicago sativa*); MF = meadow fescue (*Festuca pratense*); OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*); T = timothy (*Phleum pratense*); TF = tall fescue (*Festuca arundinacea*); WC = white clover (*Trifolium repens*); WO = winter oats (*Avena sativa*).

²Between parentheses supplement DMI as percentage of the total DMI.

³Between parentheses individual VFA expressed as molar proportion (mol/100 mol).

⁴Not available.

⁵In confinement studies, fresh cut-forage was used instead of grazed pasture.

in the propionate molar proportion (Jones-Endsley et al., 1997).

The most consistent effect of concentrate supplementation on ruminal fermentation is a reduction in ruminal $\text{NH}_3\text{-N}$ concentration. Over the 10 studies summarized in Table 10, ruminal $\text{NH}_3\text{-N}$ concentration was significantly reduced by supplementation in six (Van Vuuren et al., 1986; Carruthers and Neil, 1997; Carruthers et al., 1997; García et al., 2000; Reis and Combs, 2000b; Bargo et al., 2002a) and numerically in three (Berzaghi et al., 1996; Jones-Endsley et al., 1997; Sayers, 1999). Ruminal $\text{NH}_3\text{-N}$ concentration reduction could be associated with a higher capture of $\text{NH}_3\text{-N}$ from the highly ruminally degradable CP of pasture (Van Vuuren et al., 1986; Jones-Endsley et al., 1997; Sayers, 1999; Bargo et al., 2002a; Reis and Combs, 2000b), but also to a reduction in total CP intake because energy supplements are usually lower in CP than pasture (Berzaghi et al., 1996; Carruthers and Neil, 1997; Carruthers et al., 1997; García et al., 2000).

Overall, unsupplemented treatments (<1 kg DM/d) averaged a ruminal pH of 6.27 (range: 6 to 6.57), a $\text{NH}_3\text{-N}$ concentration of 24.7 mg/dl (range: 12.8 to 39.1 mg/dl), and a total VFA concentration of 125.2 mmol/L (range: 96.7 to 150 mmol/L); and supplemented treatments (1.1 to 10 kg DM/d) averaged a ruminal pH of 6.10 (range: 5.75 to 6.29), an $\text{NH}_3\text{-N}$ concentration of 18.3 (range: 8.7 to 32.2 mg/dl), and a total VFA concentration of 120.9 mmol/L (range: 90.3 to 151.4 mmol/L). Comparing the unsupplemented treatments with the supplemented treatments using a Student's *t*-test, supplementation reduced ruminal pH 0.08 (SE 0.03; significantly different from zero, $P < 0.01$), reduced $\text{NH}_3\text{-N}$ concentration 6.59 mg/dl (SE 1.16 mg/dl; significantly different from zero, $P < 0.01$), and increased total VFA concentration 1.95 mmol/L (SE 1.20 mmol/L; nonsignificantly different from zero, $P > 0.13$).

Type of energy supplementation. The effect of type of energy supplementation on ruminal fermentation of dairy cows on pasture is summarized in Table 11. Some studies compared starch vs. fiber-based concentrates with starch sources including corn and tapioca (Van Vuuren et al., 1986), barley, wheat, and corn (Sayers, 1999), and barley and oats (Khalili and Sairanen, 2000), and fiber sources including beet pulp (Van Vuuren et al., 1986; Khalili and Sairanen, 2000) and beet pulp plus citrus pulp (Sayers, 1999). Compared with starch-based concentrates, supplementation with fiber-based concentrates did not affect ruminal pH of dairy cows consuming moderate (approximately 5 kg DM/d; Van Vuuren et al., 1986; Khalili and Sairanen, 2000) or high (approximately 10 kg DM/d, Sayers, 1999) amounts of concentrate. No changes in ruminal $\text{NH}_3\text{-N}$ concentration were reported by Van Vuuren et al. (1986) and

Sayers (1999), whereas Khalili and Sairanen (2000) showed a reduction in this variable with the fiber-based concentrate. None of the three studies reported differences in total VFA concentrations, but Sayers (1999) found that supplementation with fiber-based concentrates increased the molar proportion of acetate and butyrate, and decreased the molar proportion of propionate. Khalili and Sairanen (2000) reported no changes in the molar proportion of any of the three major VFA.

Supplementation with a high rumen degradable grain such as barley reduced ruminal $\text{NH}_3\text{-N}$ concentration but did not affect ruminal pH or total VFA concentration compared with a low rumen degradable grain such as corn when provided as 24% of starch in a diet based on fresh cut winter oats (García et al., 2000). Barley supplementation also increased the molar proportion of propionate and reduced the proportion of butyrate (García et al., 2000). Ruminal pH and total VFA concentrations were unaffected when dry corn was substituted for processed forms of corn with higher ruminal degradability such as high moisture corn (Soriano et al., 2000; Alvarez et al., 2001), steam-rolled corn (Reis and Combs, 2000a), or steam-flaked corn (Bargo et al., 1998). Ruminal $\text{NH}_3\text{-N}$ concentration was numerically (Soriano et al., 2000) or significantly (Alvarez et al., 2001) reduced with high moisture corn. Steam-flaked corn also reduced $\text{NH}_3\text{-N}$ concentration compared with dry ground corn (Bargo et al., 1998). Reis and Combs (2000a), however, found no changes in $\text{NH}_3\text{-N}$ concentration when grazing cows were supplemented with dry ground corn or steam-rolled corn. Ruminal pH was lower when 9.1 kg DM/d of a corn-based concentrate were fed together with the pasture than when they were fed 4 h after feeding pasture (Kolver et al., 1998). Neither $\text{NH}_3\text{-N}$ concentration, nor total VFA concentration, nor molar proportion of acetate and propionate were affected by timing of supplementation (Kolver et al., 1998).

Overall, when dry corn were replaced by processed corn (Bargo et al., 1998; Reis and Combs, 2000a; Soriano et al., 2000; Alvarez et al., 2001), by higher ruminally degradable grain such as barley (García et al., 2000), or starch-based concentrates by fiber-based concentrates (Van Vuuren et al., 1986; Sayers, 1999; Khalili and Sairanen, 2000) neither ruminal pH (−0.007, SE 0.04, range: −0.16 to 0.16; Student's *t*-test, significantly different from zero; $P = 0.87$) nor total VFA concentration (−0.47 mmol/L, SE 1.74 mmol/L, range: −7.0 to 5.0; Student's *t*-test, significantly different from zero; $P = 0.79$) were affected, but $\text{NH}_3\text{-N}$ concentration was reduced 4.36 mg/dl (SE 1.37 mg/dl; Student's *t*-test, significantly different from zero; $P < 0.01$).

Protein supplementation. The effect of protein supplementation on the ruminal fermentation of dairy cows

Table 11. Effect of type of energy supplementation on ruminal fermentation of dairy cows on pasture.

Reference	Pasture ¹	Concentrate		pH	NH ₃ -N mg/dl	VFA, mmol/L			
		Type	DMI, ² kg/d			Total	Acetate ³	Propionate ³	Butyrate ³
Alvarez et al., 2001	ARG/WO	Dry cracked corn	5.7 (28%)	5.97	9.1 ^a	90.6	49.5 (NA)	24.3 (NA)	12.2 (NA)
		High moisture corn	6.4 (30%)	6.01	12.9 ^b	86.3	48.7 (NA)	21.9 (NA)	11.4 (NA)
Bargo et al., 1998	A/OG	Dry ground corn	6.2 (35%)	5.70	19.1 ^a	76.1	NA ⁴ (63.7)	NA (20.1)	NA (11.6)
		Steam-flaked corn (290 g/L) ⁵	6.6 (40%)	5.63	13.8 ^b	72.0	NA (60.9)	NA (22.8)	NA (11.6)
García et al., 2000 (Confinement) ⁶	WO	Corn (24% starch diet)	2.4 (29%)	6.02	26.9 ^a	97.3	NA (60.1)	NA (21.4 ^b)	NA (13.7 ^b)
		Barley (24% starch diet)	2.6 (35%)	6.09	19.4 ^b	90.3	NA (57.8)	NA (24.9 ^a)	NA (11.9 ^a)
Khalili and Sairanen, 2000	MF/T	Barley	4 (NA)	6.17	32.1 ^a	127.0	NA (64.1)	NA (19.1)	NA (12.5)
		Barley/oats/beet pulp	4 (NA)	6.01	21.8 ^b	132.0	NA (64.0)	NA (20.5)	NA (11.6)
Kolver et al., 1998 (Confinement) ⁶	OG	Corn based (fed with forage)	9.2 (49%)	6.06 ^a	16.3	118.0	75.3	24.7	13.5 ^a
		Corn based (fed 4 h after forage)	9.1 (47%)	6.17 ^b	18.4	114.3	72.5	24.6	12.6 ^b
Reis and Combs, 2000a	A/RC/OG	Dry ground corn (680 g/L) ⁴	9.0 (45%)	6.57	13.3	117.3	74.5	29.9	13.6 ^a
		Steam-rolled corn (591 g/L)	9.0 (45%)	6.48	12.6	120.5	72.7	32.0	15.8 ^b
Sayers, 1999	RG	Starch-based	5 to 10 (28 to 50%)	5.80	12.0	121.6	NA (56.1 ^a)	NA (26.1 ^a)	NA (13.7 ^a)
		Fiber-based	5 to 10 (28 to 50%)	5.96	13.6	122.5	NA (60.3 ^b)	NA (20.7 ^b)	NA (15.4 ^b)
Soriano et al., 2000	OG	Coarsely ground corn	6.0 (NA)	NA	31.0	NA	NA	NA	NA
		High moisture corn	6.0 (NA)	NA	26.2	NA	NA	NA	NA
Van Vuuren et al., 1986	RG	High starch concentrate	5.4 (32%)	5.90	22.1	127.0	NA	NA	NA
		Low starch concentrate	5.2 (29%)	5.90	20.4	130.0	NA	NA	NA

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹A = alfalfa (*Medicago sativa*); ARG = annual ryegrass (*Lolium multiflorum*); MF = meadow fescue (*Festuca pratense*); OG = orchardgrass (*Dactylis glomerata*); RC = red clover (*Trifolium pratense*); RG = perennial ryegrass (*Lolium perenne*); T = timothy (*Phleum pratense*); WO = winter oats (*Avena sativa*).

²Between parentheses supplement DMI as percentage of the total DMI.

³Between parentheses individual VFA expressed as molar proportion (mol/100 mol).

⁴Not available.

⁵Density.

⁶In confinement studies, fresh cut-forage was used instead of grazed pasture.

Table 12. Effect of protein supplementation on ruminal fermentation of dairy cows on pasture.

Reference	Pasture ¹	Concentrate		pH	NH ₃ -N mg/dl	VFA, mmol/L			
		Type ²	DMI, ³ kg/d			Total	Acetate ⁴	Propionate ⁴	Butyrate ⁴
Bargo et al., 2001	WO	SM (15.3, 39.2)	6.2 (34%)	5.52	21.1 ^a	129.2	NA ⁵ (57.4)	NA (23.5)	NA (13.7)
		SM (23.3, 35.8)	6.4 (31%)	5.53	28.5 ^b	133.9	NA (54.5)	NA (23.4)	NA (15.3)
		FtM (24.6, 46.3)	6.4 (33%)	5.51	19.3 ^a	127.6	NA (55.6)	NA (23.7)	NA (14.6)
Delagarde et al., 1997	RG (0 kg N/ha)	Control	0.0	6.15 ^a	4.6 ^a	101.0 ^a	NA (63.4)	NA (21.0)	NA (12.6 ^a)
		SBM (48)	2.0 (13%)	6.01 ^b	8.5 ^b	111.0 ^b	NA (63.7)	NA (20.4)	NA (13.0 ^a)
	RG (60 kg N/ha)	Control	0.0	6.26 ^c	17.7 ^c	106.0 ^c	NA (63.6)	NA (20.8)	NA (11.5 ^b)
		SBM (48)	2.0 (13%)	6.13 ^d	21.6 ^d	117.0 ^d	NA (62.8)	NA (21.2)	NA (11.9 ^b)
McCormick et al., 2001b (Confinement) ⁶	ARG	S-SBM (13.5, 43.0)	10.8 (47%)	6.19	11.1	120.8	NA (65.4)	NA (22.6)	NA (11.9 ^a)
		E-SBM (14.0, 53.6)	11.5 (49%)	6.20	10.2	113.1	NA (61.7)	NA (22.6)	NA (15.7 ^b)
Sayers, 1999 (Confinement) ⁶	RG	Control	0.0	6.33 ^a	24.9 ^a	122.8	NA (69.3 ^{ab})	NA (NA)	NA (14.3)
		SBM (10)	2.6 (15%)	6.19 ^b	20.4 ^b	132.8	NA (68.1 ^b)	NA (NA)	NA (15.3)
		SBM (34)	2.6 (15%)	6.03 ^b	28.9 ^c	145.4	NA (64.9 ^b)	NA (NA)	NA (17.4)
		SBM (10)	5.2 (31%)	6.26 ^b	31.6 ^d	144.4	NA (67.3 ^c)	NA (NA)	NA (16.3)
		SBM (34)	5.2 (29%)	6.11 ^b	45.7 ^e	148.6	NA (65.3 ^c)	NA (NA)	NA (15.5)
Schor and Gagliostro, 2001	A/RG	SBM (20.8, NA)	5.9 (30%)	5.7	25.3 ^a	119.0	NA (57.6)	NA (24.8)	NA (13.0)
		BM (22.9, NA)	5.7 (25%)	5.8	21.2 ^b	112.0	NA (58.1)	NA (24.3)	NA (13.1)

^{a,b,c,d,e}Means within reference with different superscripts differ ($P < 0.05$; unless other state; McCormick et al., 2001b $P < 0.10$ for butyrate).

¹A = alfalfa (*Medicago sativa*); ARG = annual ryegrass (*Lolium multiflorum*); RG = perennial ryegrass (*Lolium perenne*); WO = winter oats (*Avena sativa*).

²Main protein source: E-SBM = expeller soybean meal; FtM = feather meal, SBM = soybean meal; SM = sunflower meal; S-SBM = solvent soybean meal; between parentheses %CP and %RUP/CP in the concentrate, respectively.

³Between parentheses supplement DMI as percentage of the total DMI.

⁴Between parentheses individual VFA expressed as molar proportion (mol/100 mol).

⁵Not available.

⁶In confinement studies, fresh cut-forage was used instead of grazed pasture.

on pasture is presented in Table 12. Most of the studies (Sayers, 1999; Bargo et al., 2001; McCormick et al., 2001b; Schor and Gagliostro, 2001) reported no differences in ruminal pH or total VFA concentration when the content of CP in the concentrate was increased in supplemented dairy cows. Compared with pasture-only diets, supplementation with 2 kg DM/d of soybean meal reduced ruminal pH of dairy cows grazing a ryegrass fertilized with 0 or 60 kg of N/ha, which was associated with an increase in total VFA concentration (Delagarde et al., 1997).

Ruminal $\text{NH}_3\text{-N}$ concentration was increased with soybean meal supplementation compared with pasture-only diets (Delagarde et al., 1997). Ruminal $\text{NH}_3\text{-N}$ concentration was also increased as the concentrate CP content increased from 15 to 23% with 6.3 kg DM/d of supplementation (Bargo et al., 2001) and from 10 to 34% with 2.6 and 5.2 kg DM/d of supplementation (Sayers, 1999). Supplementation with concentrates of 20 to 23% CP reduced $\text{NH}_3\text{-N}$ concentration when RDP sources such as sunflower meal (Bargo et al., 2001) or soybean meal (Schor and Gagliostro, 2001) were replaced by RUP sources such as feather meal (Bargo et al., 2001) or blood meal (Schor and Gagliostro, 2001). Reduction in ruminal $\text{NH}_3\text{-N}$ concentrations were previously reported for grazing cows supplemented with treated casein (Rogers et al., 1980) or treated sunflower meal (Hamilton et al., 1992). McCormick et al. (2001b), however, found similar $\text{NH}_3\text{-N}$ concentration with the supplementation of solvent versus expeller soybean meal.

Forage supplementation. Two studies evaluated the effect of forage supplements such as corn silage (Elizalde et al., 1992) or hay (Reis and Combs, 2000a) on ruminal fermentation of dairy cows on pasture. Supplementation with 5 kg DM/d of corn silage to dairy cows grazing a winter oats pasture increased ruminal pH, but did not affect $\text{NH}_3\text{-N}$ concentration in the rumen (Elizalde et al., 1992). Ruminal pH, $\text{NH}_3\text{-N}$, and total VFA concentration were not affected when high producing dairy cows grazing a grass-legume pasture were supplemented with 3.2 kg DM/d of long alfalfa hay plus 9 kg of DM/d dry ground or steam-rolled corn (Reis and Combs, 2000a).

PASTURE IN SITU DIGESTION

Extensive reviews on the in situ technique have been published (Nocek, 1988; Vanzant et al., 1998; Noziere and Michalet-Doreau, 2000). Several studies used the in situ technique to estimate degradation of pastures commonly fed to dairy cows. Some studies were conducted in confinement with cows consuming orchardgrass hay (Elizalde et al., 1999), TMR (Hoffman et al., 1993), or fresh cut forage (Sayers, 1999; Van

Vuuren et al., 1992; Van Vuuren et al., 1993) as basal diets; others were conducted with cows grazing ryegrass (Van Vuuren et al., 1991; Sayers, 1999), orchardgrass (Bargo et al., 2002a), winter oats (Elizalde et al., 1992; Bargo et al., 2001), or legume/grass pastures (Reis and Combs, 2000a, 2000b). Form and processing of pasture samples included fresh-meat chopper (Elizalde et al., 1992, 1999; Bargo et al., 2001), dried-ground (Van Vuuren et al., 1992, 1993; Hoffman et al., 1993), frozen masticate-ground (Reis and Combs, 2000a; 2000b), and fresh-cut to 1-cm size (Van Vuuren et al., 1991; Sayers, 1999; Bargo et al., 2002a).

López et al. (1999) compared different mathematical models to analyze in situ data. For DM and CP most of the studies used a first-order model (Ørskov and MacDonald, 1979) with a soluble fraction (a) and an insoluble potentially degradable fraction (b) degraded at a constant rate (c) that describe the potentially degradable fraction (**PD**): $\text{PD} = a + b(1 - e^{-ct})$, where t refers to time. The effective degradability (**ED**) of DM and CP was generally estimated using the following equation: $\text{ED} = a + b(c / (c + kp))$, where kp corresponds to rate of passage assumed (6 %/h). In some cases for DM and in most cases for NDF, the models included a lag time.

Effect of Species and Maturity, and N Fertilization on In Situ Pasture Digestion

Studies that have evaluated the in situ DM, CP, and NDF digestion of pasture are shown in Table 13. Two studies (Hoffman et al., 1993; Elizalde et al., 1999) evaluated ruminal DM, CP, and NDF degradability of different species commonly used for dairy cows at different stages of maturity. Hoffman et al. (1993) compared in situ degradation of alfalfa, birdsfoot trefoil, red clover at late vegetative, late bud, and midbloom, and brome-grass, orchardgrass, ryegrass, timothy, and quackgrass at second node, boot, and full inflorescence. The CP content decreased, and NDF content increased with maturity, but those changes were larger in the grasses (24.4 to 10.6% CP, 41.5 to 67.2% NDF) than in the legumes (26.9 to 15.7% CP, 26.5 to 47.3% NDF). Legumes tended to have a larger ED of DM than grasses at all maturity stages, except that the ED of DM of ryegrass was similar to that of legumes at all stages of maturity. With maturity, rate of degradation of DM decreased from 20 to 13%/h for the legumes, and from 11 to 2%/h for the grasses. Effective degradability of CP of legumes did not differ among species. Among grasses, ryegrass had the highest values of ED of CP. With maturity, CP rate of degradation decreased from 40 to 7%/h for the legumes, and from 26 to 3 %/h for

Table 13. Effect of species and maturity and N fertilization on in situ DM, CP, and NDF digestion of pastures.

Reference	Basal diet ²	Sample	Treatment	DM ¹				CP ¹				NDF ¹			
				a	b	c	ED	a	b	c	ED	a	b	c	ED
Elizalde et al., 1999 (Confinement) ³	OG hay	Fresh Food chopper	Alfalfa												
			Mid vegetative	35.5 ^a	48.0	17.6 ^a	71.2 ^a	40.2	53.6 ^a	19.6 ^a	81.1 ^a	NA ⁴	NA	NA	NA
			Early bud	49.9 ^b	39.1	14.3 ^a	77.3 ^b	41.3	53.1 ^a	16.1 ^{ab}	79.8 ^a	NA	NA	NA	NA
			Early flowering	32.0 ^a	41.2	11.8 ^b	59.1 ^c	40.1	48.5 ^{ab}	16.7 ^{ab}	74.9 ^b	NA	NA	NA	NA
			Late flowering	29.1 ^c	43.6	11.4 ^b	57.5 ^c	41.3	47.1 ^b	12.2 ^b	72.9 ^b	NA	NA	NA	NA
			Bromegrass												
			Tillering	24.3	64.0 ^a	11.5 ^a	66.1 ^a	32.3 ^b	63.8 ^a	16.8 ^a	79.2 ^a	NA	NA	NA	NA
			Stem elongation	18.6	64.3 ^a	6.6 ^b	52.1 ^b	27.1 ^{bc}	64.3 ^a	10.3 ^a	67.6 ^b	NA	NA	NA	NA
			Heading	20.8	55.4 ^a	7.2 ^b	50.9 ^b	36.2 ^b	51.2 ^b	11.4 ^{ab}	69.7 ^b	NA	NA	NA	NA
			Flowering	19.8	43.2 ^b	5.6 ^b	40.2 ^c	45.6 ^a	35.7 ^c	8.9 ^b	67.0 ^b	NA	NA	NA	NA
			Tall fescue												
			Tillering	33.8 ^b	53.8 ^a	8.6 ^a	65.5 ^a	43.8 ^c	49.2 ^a	16.9 ^a	79.8 ^{ab}	NA	NA	NA	NA
			Stem elongation	28.4 ^b	58.2 ^a	7.4 ^b	60.3 ^b	46.8 ^b	46.0 ^a	13.3 ^a	82.4 ^a	NA	NA	NA	NA
			Heading	41.1 ^a	40.6 ^b	5.4 ^{bc}	60.0 ^b	55.8 ^a	32.2 ^b	10.7 ^b	76.1 ^b	NA	NA	NA	NA
			Flowering	23.3 ^{bc}	51.0 ^c	2.7 ^c	38.1 ^c	52.5 ^{ab}	26.7 ^b	11.0 ^a	69.9 ^c	NA	NA	NA	NA
Hoffman et al., 1993 (Confinement) ³	TMR Indoors	Dried Ground	Alfalfa												
			Late vegetative	46.7	37.3	15.0	73.4	62.5	28.5	18.0	83.9	15.8	50.0	11.0	47.9
			Late bud	33.4	37.3	16.0	60.3	44.8	41.1	23.0	77.4	6.0	42.7	9.0	32.0
			Midbloom	32.5	33.4	13.0	55.2	48.2	30.8	21.0	72.1	6.8	40.6	7.0	28.6
			Birdsfoot trefoil												
			Late vegetative	48.5	37.4	20.0	77.2	54.5	38.0	31.0	86.3	8.4	55.5	12.0	45.9
			Late bud	40.2	38.4	18.0	69.0	48.6	40.9	40.0	84.1	2.3	50.3	15.0	38.0
			Midbloom	33.8	33.3	15.0	57.7	52.1	30.8	20.0	75.1	0.0	42.5	8.0	24.9
			Red clover												
			Late vegetative	44.4	45.8	18.0	78.1	52.8	42.2	25.0	86.4	0.0	52.5	5.0	23.4
			Late bud	38.5	44.6	13.0	68.7	48.6	40.9	40.0	84.1	4.2	41.4	3.0	19.2
			Midbloom	35.5	40.7	14.0	64.2	52.1	30.8	20.0	75.1	6.6	28.0	8.0	22.3
			Bromegrass												
			Second node	36.3	51.7	6.0	62.0	45.1	47.5	11.0	76.0	2.4	81.2	6.0	41.7
			Boot	32.7	49.4	5.0	55.5	46.1	43.1	9.0	72.0	1.3	73.5	5.0	35.1
			Full inflorescence	26.1	44.8	3.0	41.0	44.1	38.7	7.0	64.4	1.6	63.4	3.0	20.5
			Orchardgrass												
			Second node	39.0	46.3	10.0	67.2	51.5	40.7	18.0	81.7	6.4	72.9	8.0	46.6
			Boot	34.0	47.3	8.0	60.2	46.1	41.7	15.0	75.2	0.0	73.2	7.0	39.8
			Full inflorescence	28.7	44.9	7.0	52.3	44.3	39.9	13.0	71.4	8.8	62.7	6.0	40.2
			Perennial ryegrass												
			Second node	46.7	45.1	11.0	75.8	62.0	33.6	22.0	88.5	15.0	72.3	9.0	58.1
			Boot	42.5	45.7	9.0	69.4	60.8	30.7	26.0	85.7	11.6	71.6	7.0	50.2
			Full inflorescence	32.0	45.8	5.0	52.7	45.9	33.2	12.0	67.8	7.6	65.3	4.0	34.8
			Quackgrass												
			Second node	37.0	49.2	7.0	62.7	52.2	39.1	14.0	79.5	3.2	78.8	6.0	41.2
			Boot	23.8	53.2	3.0	43.3	36.6	41.5	12.0	63.9	0.0	73.1	3.0	26.5
			Full inflorescence	22.0	45.3	2.0	35.0	38.4	37.7	3.0	48.8	1.2	43.8	4.0	19.0
			Timothy												
			Second node	37.1	51.3	9.0	68.1	59.5	34.2	16.0	84.4	29.4	61.9	2.0	46.8
			Boot	30.9	46.7	5.0	52.5	55.8	22.1	20.0	71.6	11.8	50.8	3.0	27.6
			Full inflorescence	27.1	39.3	4.0	43.6	44.9	19.6	7.0	55.1	13.4	30.6	4.0	26.4

Table 13 (continued). Effect of species and maturity and N fertilization on in situ DM, CP, and NDF digestion of pastures.

Reference	Basal diet ²	Sample	Treatment	DM ¹				CP ¹				NDF ¹			
				a	b	c	ED	a	b	c	ED	a	b	c	ED
Van Vuuren et al., 1991	RG	Fresh Cut 1-cm	Perennial ryegrass												
			5 d after fertilization												
			0 kg N/ha	21.0	70.0	4.7	51.7	NA	NA	NA	NA	NA	NA	NA	NA
			250 kg N/ha	22.0	73.0	5.6	57.2	NA	NA	NA	NA	NA	NA	NA	NA
			400 kg N/ha	18.0	77.0	7.0	59.5	NA	NA	NA	NA	NA	NA	NA	NA
			700 kg N/ha	19.0	74.0	7.8	60.8	NA	NA	NA	NA	NA	NA	NA	NA
			9 d after N fertilization												
			0 kg N/ha	7.0	72.0	4.9	39.4	NA	NA	NA	NA	NA	NA	NA	NA
			250 kg N/ha	19.0	68.0	6.3	53.8	NA	NA	NA	NA	NA	NA	NA	NA
			400 kg N/ha	13.0	77.0	5.0	48.0	NA	NA	NA	NA	NA	NA	NA	NA
			700 kg N/ha	14.0	78.0	7.2	56.5	NA	NA	NA	NA	NA	NA	NA	NA
			13 d after fertilization												
			0 kg N/ha	14.0	81.0	7.8	59.8	NA	NA	NA	NA	NA	NA	NA	NA
			250 kg N/ha	12.0	82.0	8.4	59.8	NA	NA	NA	NA	NA	NA	NA	NA
			400 kg N/ha	9.0	86.0	9.8	62.3	NA	NA	NA	NA	NA	NA	NA	NA
			700 kg N/ha	12.0	84.0	10.1	64.7	NA	NA	NA	NA	NA	NA	NA	NA
Van Vuuren et al., 1992 (Confinement) ³	Fresh forage	Dried Ground	June-July												
			275 kg N/ha	40.4	53.1 ^a	6.1	67.2	47.2	47.5 ^a	9.2	76.0	0.0	90.9	4.9	40.9
			500 kg N/ha	40.4	54.7 ^b	6.9	69.7	53.1	43.3 ^b	9.0	79.1	0.0	92.6	5.6	44.7
			September-October												
			275 kg N/ha	34.2	57.9 ^a	4.7 ^a	59.6	40.3	53.2 ^a	6.4 ^a	67.8	0.0	89.5	4.2 ^a	36.9
			500 kg N/ha	46.3	49.4 ^b	6.8 ^b	72.5	47.5	48.8 ^b	9.1 ^b	76.9	0.0	93.5	6.6 ^b	49.0
Van Vuuren et al., 1993 (Confinement) ³	Fresh forage	Dried Ground	Perennial ryegrass												
			June	34.6	60.3 ^b	5.1 ^b	62.3	45.1	50.9 ^b	9.1 ^a	75.8	0.0	90.7	4.3	37.9
			July	35.8	57.7 ^c	5.0 ^b	62.0	42.3	52.8 ^a	8.9 ^a	73.8	0.0	89.7	4.4	38.0
			August	43.1	52.9 ^d	5.2 ^b	67.7	45.3	50.4 ^b	7.2 ^b	72.8	0.0	91.7	4.8	40.8
			September	33.9	61.5 ^a	5.9 ^a	64.4	42.1	53.5 ^a	8.6 ^a	73.6	0.0	93.5	5.4	44.3

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹a = soluble fraction (%); b = insoluble potentially degradable fraction (%); c = rate of degradation (%/h) of the b fraction; ED = effective degradability (%): $ED = A + B \times (c / (c + kp))$, where kp = rate of passage.

²OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*).

³In confinement studies, fresh cut-forage was used instead of grazed pasture.

⁴Not available.

the grasses. For NDF degradation, legumes generally were lower in degraded NDF than grasses with ryegrass having the highest ruminally degraded NDF of all species at all stages of maturity. With maturity, rate of degradation of NDF decreased from 15 to 3%/h for the legumes, and from 9 to 2%/h for the grasses (Hoffman et al., 1993).

Elizalde et al. (1999) compared the in situ DM and CP degradation of alfalfa at vegetative, early bud, early flowering, and late flowering, and bromegrass and tall fescue at tillering, stem elongation, heading, and flowering. Content of NDF content increased, whereas content of CP content decreased with maturity in both the alfalfa (34.8 to 46.0% NDF, 22.6 to 15.8% CP) and the grasses (52.2 to 66.9% NDF, 25.8 to 8.2% CP). Alfalfa had a higher soluble fraction of DM than grasses, and the rate of DM degradation in alfalfa was double the rate in grasses (13.7 vs. 6.7%/h). Effective degradability of DM decreased with maturity. For CP, however, alfalfa and grasses did not differ in the soluble or the insoluble potentially degradable fractions, while the rate of CP degradation tended to be higher in alfalfa than in the grasses (16.2 vs. 12.4%/h). The ED of CP was not different between alfalfa and grasses. Measures of CP degradation were less influenced by maturity than those for DM, especially in grasses (Elizalde et al., 1999).

Two studies evaluated the effect of N fertilization (275 vs. 500 kg/ha; Van Vuuren et al., 1992) and season (June, July, August, and September; Van Vuuren et al., 1993) on in situ ryegrass degradation. For DM, soluble fraction was not affected by N fertilization, while the insoluble potentially degradable fraction increased with fertilization during the summer, but decreased during the fall (Van Vuuren et al., 1992). Rate of DM degradation was increased with fertilization amount during the fall (4.7 vs. 6.8%/h). For CP, soluble fraction was not affected by fertilization or season, while insoluble potentially degradation fraction decreased with fertilization during the summer and the fall (Van Vuuren et al., 1992). Rate of degradation of CP was increased with fertilization during the fall (6.4 vs. 9.1%/h). For NDF, fertilization amount increased rate of degradation (4.2 vs. 6.6%/h; Van Vuuren et al., 1992). Soluble fraction of DM and CP were not affected by season (Van Vuuren et al., 1993). Insoluble potentially degradable fraction and rate of degradation of DM and CP were lower during July and August and higher during June and September. For NDF, insoluble potentially degradable fraction and rate of degradation (4.7%/h) did not differ with season (Van Vuuren et al., 1993).

Effect of Supplementation on In Situ Pasture Digestion

Several studies have evaluated the effect of supplementation on in situ degradation of pasture (Table 14).

In four of seven studies, dairy cows were supplemented with energy supplements such as corn-based concentrates (Sayers, 1999; Reis and Combs, 2000a, 2000b; Bargo et al., 2002a), steam-rolled corn (Reis and Combs, 2000a), and fiber-based concentrates (Sayers, 1999). Amount of supplements range from 0 to 10 kg DM/d, with two studies (Reis and Combs, 2000b; Bargo et al., 2002a) including pasture-only diet treatments. In two of seven studies, dairy cows were supplemented with concentrates that differed in content and source of CP (Bargo et al., 2001) or with different amounts of concentrates that differed in CP content (Sayers, 1999), including a pasture-only diet. One study (Elizalde et al., 1992) supplemented dairy cows with corn silage.

Compared with a pasture-only diet treatment, the supplementation with 10 kg DM/d of corn reduced the insoluble potentially degradable DM fraction of pasture, without affecting the soluble fraction, rate of degradation, and the effective degradability of DM (Reis and Combs, 2000b). Supplementation with 5 kg DM/d of corn did not, however, affect any of the degradation variables of pasture (Reis and Combs, 2000b). Compared with pasture-only diet treatments, rate of degradation of pasture DM was reduced from 6.8 to 5.4%/h with concentrate supplementation, while neither lag time, nor the soluble fraction, nor insoluble potentially degradable fraction of DM were affected by supplementation (Bargo et al., 2002a). Pasture NDF showed also a reduction in the rate of degradation (5.1 vs. 4.1%/h) with concentrate supplementation compared with pasture-only diets (Bargo et al., 2002a). Supplementation with 9 kg DM/d of a faster ruminally degradable form of corn (steam-rolled) reduced the rate of degradation of pasture DM from 12.2 to 11.4%/h compared with supplementation with a slower ruminally degradable form of corn (dry corn; Reis and Combs, 2000a). Form of corn did not affect the soluble, insoluble potentially degradable, or effective degradability of DM of pasture (Reis and Combs, 2000a). Sayers (1999) reported that supplementation with 5 or 10 kg DM/d of a starch or a fiber-based concentrate did not affect rate or extent of degradation of DM or CP of ryegrass.

Compared with pasture-only diets, supplementation with 2.6 or 5.2 kg DM/d of concentrate of 10 or 34% CP did not affect soluble, insoluble potentially degradable fractions, or rate of degradation of pasture DM (Sayers, 1999). Pasture CP degradation was not affected by supplementation either (Sayers, 1999). Increasing the CP content from 15 to 23% or replacing a RDP source (sunflower meal) by a RUP source (feather meal) in the concentrate did not affect soluble fraction, insoluble potentially degradable fraction, rate of degradation, or effective degradability of DM, CP, or NDF of winter oats (Bargo et al., 2001). Supplementation with 5 kg

Table 14. Effect of supplementation on in situ DM, CP, and NDF digestion of pastures.

Reference	Basal diet ²	Sample	Supplement		DM ¹				CP ¹				NDF ¹				
			Type	DMI, kg/d	a	b	c	ED	a	b	c	ED	L	a	b	c	ED
Bargo et al., 2001	WO	Fresh Meat chopper	Sunflower meal (15.3, 39.2)	6.2	57.3	33.3	7.8	76.1	62.4	31.7	9.8	82.1	0.00	0.0	82.5	5.2	NA ³
			Sunflower meal (23.3, 35.8)	6.4	57.4	33.2	8.1	76.4	61.7	32.9	10.2	82.4	0.61	0.0	81.9	4.9	NA
			Feather meal (24.6, 46.3)	6.4	58.3	31.4	9.4	77.4	63.6	29.3	9.8	81.8	0.00	0.0	80.7	5.3	NA
Bargo et al., 2002a	OG	Fresh 1 cm	Mineral/vitamin mix	0.8	20.7	57.7	7.6 ^a	46.7	NA	NA	NA	NA	3.33	6.6	64.6	5.5 ^a	28.3
			Corn-based concentrate	8.6	26.3	56.4	5.3 ^b	50.3	NA	NA	NA	NA	4.88	10.6	68.8	4.5 ^b	28.7
			Mineral/vitamin mix	0.7	27.7	52.9	6.0 ^a	47.4	NA	NA	NA	NA	4.75	11.5	65.9	4.6 ^a	28.4
			Corn-based concentrate	8.7	22.1	59.0	5.4 ^b	45.1	NA	NA	NA	NA	4.38	6.9	74.7	3.6 ^b	24.6
Elizalde et al., 1992	WO	Fresh Meat mincer	Control	0.0	NA	NA	NA	NA	41.8	58.2	4.1	65.3	1.4 ^a	0.0	68.3	4.4	28.9
			Corn silage	5.0	NA	NA	NA	NA	34.7	65.3	4.6	63.0	5.8 ^b	0.0	67.6	5.3	31.7
Reis and Combs, 2000a	A/RC/OG	Frozen masticates Ground	Dry corn	9.0	47.5	40.8	12.1 ^a	74.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
			Dry corn + hay	9.0 + 3.2	49.0	38.8	12.2 ^a	75.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
			Steam-rolled corn	9.0	47.8	40.8	11.4 ^b	74.5	NA	NA	NA	NA	NA	NA	NA	NA	NA
			Steam-rolled corn + hay	9.0 + 3.2	46.8	42.3	11.3 ^b	74.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Reis and Combs, 2000b	A/RC/RG	Frozen masticates Ground	Corn-based	0.0	47.9	39.4 ^a	10.5	73.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
				5.0	48.8	37.6 ^{ab}	10.1	72.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
				10.0	48.6	36.3 ^b	11.1	72.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sayers, 1999 (Confinement) ⁴	RG	Fresh 1 cm	Control	0.0	26.8	63.6	7.6	58.0	31.8	64.5	9.9	67.0	NA	NA	NA	NA	NA
			Concentrate 10%CP	2.6	26.1	64.2	7.5	56.0	30.2	65.6	10.1	66.0	NA	NA	NA	NA	NA
			Concentrate 34%CP	2.6	26.8	62.8	6.5	55.0	29.9	66.2	9.0	65.0	NA	NA	NA	NA	NA
			Concentrate 10%CP	5.2	27.0	63.9	6.7	56.0	30.5	65.1	9.4	65.0	NA	NA	NA	NA	NA
			Concentrate 34%CP	5.2	26.5	63.0	6.5	54.0	29.7	66.3	8.4	63.0	NA	NA	NA	NA	NA
Sayers, 1999	RG	Fresh 1 cm	Starch-based	5.0	21.9	71.6	6.7	54.0	7.3	92.0	9.4	57.0	NA	NA	NA	NA	NA
			Fiber-based	5.0	22.5	68.4	7.8	55.0	8.1	90.5	9.9	57.0	NA	NA	NA	NA	NA
			Starch-based	10.0	23.9	65.4	6.1	50.0	15.2	83.0	7.9	56.0	NA	NA	NA	NA	NA
			Fiber-based	10.0	21.9	67.2	6.8	52.0	9.2	89.1	9.0	56.0	NA	NA	NA	NA	NA

^{a,b,c}Means within reference with different superscripts differ ($P < 0.05$).

¹L = lag time, h; a = soluble fraction (%); b = insoluble potentially degradable fraction (%); c = rate of degradation (%/h) of the b fraction; ED = effective degradability (%): $ED = A + B \times (c / (c + kp))$, where kp = rate of passage

²A = alfalfa (*Medicago sativa*), OG = orchardgrass (*Dactylis glomerata*), RC = red clover (*Trifolium pratense*), RG = perennial ryegrass (*Lolium perenne*), WO = winter oats (*Avena sativa*).

³Not available.

⁴In confinement studies, fresh cut-forage was used instead of grazed pasture.

DM/d of corn silage did not affect winter oats pasture CP degradation, but increased the lag time of NDF pasture degradation from 1.4 to 5.8 h (Elizalde et al., 1992).

In conclusion, supplementation including corn-based concentrates (Sayers, 1999; Reis and Combs, 2000a, 2000b; Bargo et al., 2002a), fiber-based concentrates (Sayers, 1999), concentrates different CP content (Sayers, 1999; Bargo et al., 2001), or corn silage (Elizalde et al., 1992) did not affect in situ ruminal digestion of pasture. Only when large amounts of corn-based concentrates (>8 kg DM/d) were supplemented, degradation rate of pasture was reduced (Reis and Combs, 2000a; Bargo et al., 2002a).

POSTRUMINAL DIGESTION OF GRAZING DAIRY COWS

Studies on digestion of fresh or conserved forage for ruminants have been extensively reviewed by Beaver et al. (2000). Few studies have reported postruminal digestion of nutrients of supplemented dairy cows on pasture because of methodology problems with grazing. Some studies evaluated site and extent of digestion of pasture with grazing cows (Berzaghi et al., 1996; Delagarde et al., 1997; Jones-Endsley et al., 1997), whereas others were conducted in confinement with cows fed fresh-cut forage (Van Vuuren et al., 1993; O'Mara et al., 1997; García et al., 2000).

To compare the different studies, we selected common measures to express OM, NDF, and N digestion. Digestion of OM was expressed as total tract apparent digestibility (**TTAD**, %), ruminal apparent digestibility as proportion of OM intake (**RAD**, % OMI), and ruminal apparent digestibility as proportion of total OM digested (**RADD**, % OMD). Digestion of NDF was expressed as TTAD (%) and ruminal apparent digestibility as proportion of total NDF digested (RADD, % NDFD). Digestion of N was expressed as flows of NAN (g/d, % N intake), nonammonia nonmicrobial nitrogen (**NANMN**, g/d, % N intake), and microbial N (**MN**, g/d).

Postruminal Digestion of Dairy Cows on Pasture-Only Diets

Studies that reported OM, NDF, and N site of digestion of dairy cows on pasture-only diets are presented in Table 15. Holden et al. (1994) compared N digestion of nonlactating dairy cows grazing orchardgrass or fed orchardgrass as hay or silage. Intake of N and flow of total N, NAN, and MN were not affected by the form of orchardgrass. Total N flow (NAN plus $\text{NH}_3\text{-N}$ flow), as percentage of total N intake, averaged 63, 81, and 75% for cows grazing, fed hay, and fed silage, respec-

tively, indicating higher N losses in the rumen of grazing cows (Holden et al., 1994).

Nutrient digestion of cows fed winter oats harvested in autumn, early winter, and winter at vegetative stage, early spring at initiation of stem elongation, and late spring at flowering have been reported by Elizalde et al. (1994, 1996). Total OMI decreased from autumn to late spring. The highest TTAD of OM was found in autumn, the lowest in late spring, and intermediate in winter and early spring (Elizalde et al., 1994). Total tract apparent digestibility of NDF was highest in autumn and lowest in late spring; however, RADD was not affected by maturity (Elizalde et al., 1994). Flow of NAN to the small intestine was higher in autumn and winter than in spring, partially because of a higher N intake. However, losses of N in the rumen were higher in autumn and winter as indicated by higher ruminal $\text{NH}_3\text{-N}$ concentration (32.6 mg/dl in autumn, 17.3 mg/dl in winter, 5.1 mg/dl in spring) and lower NAN, as percentage of total N intake, during autumn and winter (68 vs. 112%; Elizalde et al., 1996). Degradability of N was higher in autumn and winter than in spring. Flow of microbial N did not differ across harvesting date (Elizalde et al., 1996).

Two studies (Van Vuuren et al., 1992; Peyraud et al., 1997) compared nutrient digestion of ryegrass pasture fertilized with N. Fertilization increased CP content of pasture from 10.6 to 15.0% when fertilization was increased from 0 to 80 kg N/ha (Peyraud et al., 1997), and from 17.1 to 20.4% when fertilization was increased from 275 to 500 kg N/ha (Van Vuuren et al., 1992). Organic matter intake was not affected by fertilization in two of three experiments (Peyraud et al., 1997; Van Vuuren et al., 1992), but increased OM intake in one experiment (Van Vuuren et al., 1992). Fertilization increased TTAD of OM in the study of Peyraud et al. (1997), while RADD was not affected in either of the two studies (Van Vuuren et al., 1992; Peyraud et al., 1997). In the study of Peyraud et al. (1997), fertilization did not affect total NDF intake but increased TTAD of NDF. On the other hand, Van Vuuren et al. (1992) reported an increased intake of NDF in one experiment but not in other, without changes in TTAD with fertilization. Both studies reported close to 100% RADD of NDF regardless of the fertilization amount (Van Vuuren et al., 1992; Peyraud et al., 1997). Fertilization increased N intake by 40% in both studies (Van Vuuren et al., 1992; Peyraud et al., 1997), which increased the flow of NAN in one study (Peyraud et al., 1997) but not in the other (Van Vuuren et al., 1992). When expressed as a percentage of N intake, NAN was reduced by fertilization in both studies (Van Vuuren et al., 1992; Peyraud et al., 1997), indicating higher losses as $\text{NH}_3\text{-N}$ with fertilization. Flow of MN showed inconsistent re-

Table 15. Effect of maturity and N fertilization on OM, NDF, and N digestion of dairy cows on pasture.

Reference	Pasture ⁴	Treatment	OM digestion ¹				NDF digestion ²			N digestion ³			
			OMI kg/d	TTAD %	RAD %	RADD %	NDFI kg/d	TTAD %	RADD %	NI g/d	NAN g/d (% NI)	NANMN g/d (% NI)	MN g/d
Elizalde et al., 1994 (Confinement) ⁷	WO	Autumn	16.5 ^a	76 ^a	NA ⁵	70.0	9.5 ^a	66.0 ^a	95	0.82 ^{a,6}	0.46 ^a (56 ^c)	NA	0.30
		Early winter	14.6 ^b	70 ^b	NA	67.0	7.6 ^{ab}	56.0 ^{ab}	80	0.57 ^b	0.46 ^a (81 ^{bc})	NA	0.31
		Late winter	16.0 ^{ab}	74 ^{ab}	NA	64.0	8.0 ^{ab}	66.0 ^a	80	0.63 ^b	0.43 ^a (68 ^c)	NA	0.30
		Early spring	15.9 ^{ab}	72 ^{ab}	NA	64.0	7.2 ^b	56.0 ^{ab}	85	0.33 ^c	0.38 ^{ab} (11.5 ^a)	NA	0.27
		Late spring	11.3 ^c	63 ^c	NA	63.0	6.6 ^b	51.0 ^b	80	0.23 ^c	0.25 ^b (109 ^{ab})	NA	0.20
Holden et al., 1994	OG	Pasture	NA	NA	NA	NA	NA	NA	NA	351	205 (58.3)	NA	162
		Hay	NA	NA	NA	NA	NA	NA	NA	328	253 (77.3)	NA	127
		Silage	NA	NA	NA	NA	NA	NA	NA	341	240 (70.4)	NA	150
Peyraud et al., 1997 (Confinement) ⁷	RG	High N (80 kg N/ha)	13.9	81.4 ^a	NA	70.8	7.9	78.3 ^a	101	367 ^a	366 ^a (100)	NA	234
		Low N (0 kg N/ha)	14.0	79.3 ^b	NA	72.8	7.4	71.8 ^b	102	263 ^b	346 ^b (132)	NA	240
Van Vuuren et al., 1992 (Confinement) ⁷	RG	June-July											
		275 kg N/ha	15.1	NA	63.6	79.6	6.3 ^a	78.7	103	458	371 (81.0)	NA	208
		500 kg N/ha	12.1	NA	64.4	80.3	4.7 ^b	79.0	103	444	307 (69.1)	NA	188
		September-October											
		275 kg N/ha	11.6 ^a	NA	64.8	83.1	4.9	78.2	104	344 ^a	262 (76.2)	NA	107 ^a
		500 kg N/ha	13.5 ^b	NA	68.1	83.0	4.8	81.6	103	478 ^b	309 (64.6)	NA	175 ^b

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$).

¹OMI = total OM intake; TTAD = total tract apparent digestibility; RAD = ruminal apparent digestibility (% of intake); RADD = ruminal apparent digestibility (% of total digested).

²NDFI = NDF intake; TTAD = total tract apparent digestibility; RADD = ruminal apparent digestibility (% of total digested).

³NI = N intake; NAN = nonammonia N; NANMN = nonammonia nonmicrobial N; MN = microbial N.

⁴OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*); WO = winter oats (*Avena sativa*).

⁵Not available.

⁶Data expressed in g/kg BW.

⁷In confinement studies, fresh cut-forage was used instead of grazed pasture.

sults with increased flow at the higher fertilization amount (Van Vuuren et al., 1992) or no changes (Peyraud et al., 1997).

Effect of Supplementation on Postruminal Digestion of Dairy Cows on Pasture

The effects of supplementation on OM, NDF, and N site of digestion of dairy cows on pasture are summarized in Table 16. Four studies evaluated the effect of energy supplementation with corn (Berzaghi et al., 1996; García et al., 2000), barley (García et al., 2000), beet pulp (O'Mara et al., 1997), and starch or fiber-based concentrates (Van Vuuren et al., 1993). Two studies evaluated protein supplementation such as 2 kg DM/d of soybean meal compared with pasture-only diets (Delagarde et al., 1997) or CP content (12 vs. 16%) in the concentrate supplemented at 6.4 or 9.6 kg DM/d (Jones-Endsley et al., 1997).

Total OM intake was not affected by energy supplementation (Van Vuuren et al., 1992; Berzaghi et al., 1996; O'Mara et al., 1997; García et al., 2000), indicating the high SR that ranged from 0.6 to 1 kg pasture/kg concentrate. Total OM intake increased as the amount of concentrate increased from 5.6 to 8.4 kg DM/d (Jones-Endsley et al., 1997). While Berzaghi et al. (1996) reported a numerical reduction in TTAD of OM with 5.4 kg DM/d of corn, other studies did not find changes in TTAD of OM with supplementation of 2.5 kg DM/d of grain (García et al., 2000), 7.1 kg DM/d of concentrate (Van Vuuren et al., 1993), 2.7 kg DM/d of beet pulp (O'Mara et al., 1997), or with the increase of concentrate from 5.6 to 8.4 kg/d (Jones-Endsley et al., 1997). Supplementation with corn (Berzaghi et al., 1996) or a starch-based concentrate (Van Vuuren et al., 1993) reduced RAD of OM. García et al. (2000) and O'Mara et al. (1997), however, did not report changes in RAD of OM with corn or barley and beet pulp supplementation, respectively.

Energy supplementation reduced intake of NDF in some studies (Van Vuuren et al., 1993; García et al., 2000) but did not in another (Berzaghi et al., 1996). Compared to pasture-only diets, supplementation with cracked corn (Berzaghi et al., 1996), a high degradable grain as barley (García et al., 2000), or a starch-based concentrate (Van Vuuren et al., 1993) reduced TTAD of NDF. Supplementation with a slowly degradable grain as corn (García et al., 2000) or a fiber-based concentrate (Van Vuuren et al., 1993) did not affect TTAD of NDF compared with pasture-only diets. Increasing the amount of concentrate from 5.6 to 8.4 kg DM/d increased TTAD of NDF (Jones-Endsley et al., 1997). Supplementation with a starch-based concentrate did

not affect RADD of NDF in two studies (Berzaghi et al., 1996; García et al., 2000), but reduced it in another (Van Vuuren et al., 1993).

Intake of N was reduced in most of the studies by supplementation (Van Vuuren et al., 1993; Berzaghi et al., 1996; García et al., 2000) but without affecting the flows of NAN, NANMN, or MN. Supplementation increased numerically (Van Vuuren et al., 1993; Berzaghi et al., 1996) or significantly (García et al., 2000) the NAN as percentage of N intake, which indicates lower losses of $\text{NH}_3\text{-N}$. Pasture showed high degradability in the rumen (>65%) (Berzaghi et al., 1996; O'Mara et al., 1997; García et al., 2000). Total OM intake and TTAD of OM were increased with 2 kg DM/d of soybean meal supplementation (Delagarde et al., 1997) and by increasing the CP content of concentrate from 12 to 16% CP (Jones-Endsley et al., 1997). Intake of NDF and TTAD of NDF was increased as the content of CP increased in the concentrate (Jones-Endsley et al., 1997). Protein supplementation increased N intake and flows of NAN (Delagarde et al., 1997; Jones-Endsley et al., 1997) and NANMN (Jones-Endsley et al., 1997), but did not affect flow of MN (Jones-Endsley et al., 1997).

In conclusion, supplementation with energy concentrates (Van Vuuren et al., 1993; Berzaghi et al., 1996; O'Mara et al., 1997; García et al., 2000) reported similar TTAD of OM with reductions in TTAD of NDF if some cases (Van Vuuren et al., 1993; Berzaghi et al., 1996). Intake of N was reduced by supplementation because of the SR close to 1 kg/kg but did not affect flows of NAN, NANMN, or MN (Van Vuuren et al., 1993; Berzaghi et al., 1996; O'Mara et al., 1997; García et al., 2000). Protein supplementation increased TTAD of OM (Delagarde et al., 1997; Jones-Endsley et al., 1997) and NDF (Jones-Endsley et al., 1997). Protein supplementation also increased N intake and flows of NAN and NANMN without affecting MN (Delagarde et al., 1997; Jones-Endsley et al., 1997).

CONCLUSIONS

Total DMI of dairy cows on pasture-only diets is lower than total DMI of dairy cows consuming TMR or pasture plus supplements, indicating that high producing cows on pasture-based diets need to be supplemented to achieve their genetic potential for DMI. Substitution rate, or the reduction in pasture DMI per kilogram of supplement, is a major factor explaining the variation seen in MR to supplementation. There is a negative relationship between SR and MR; i.e., when SR is large (small increase in total DMI), the MR is low. Compared with pasture-only diets, increasing the amount of concentrate supplementation increased total DMI 24%, milk production 22%, and milk protein percentage 4%,

Table 16. Effect of supplementation on OM, NDF, and N digestion of dairy cows on pasture.

Reference	Pasture ⁴	Supplement		OM digestion ¹				NDF digestion ²			N digestion ³			
		Type	DMI kg/d	OMI kg/d	TTAD %	RAD % OMI	RADD % OMD	NDFI kg/d	TTAD %	RADD %	NI g/d	NAN g/d (% NI)	NANMN g/d (% NI)	MN g/d
Berzaghi et al. 1996	TF/OG/WC	Control	0.0	13.0	71.9 ^a	48.9 ^a	68.1	7.4	70.4 ^a	88.1	522 ^a	371 (71.1)	128 (24.9)	243
		Cracked corn	5.4	15.2	69.9 ^b	43.3 ^b	62.3	6.2	64.5 ^b	82.6	391 ^b	396 (84.1)	123 (26.2)	273
Delagarde et al. 1997	RG (0 kg N/ha)	Control	0.0	13.0 ^a	77.8 ^a	NA ⁵	68.0	NA	NA	NA	309 ^a	394 ^a (127.5 ^a)	NA	NA
		Soybean meal	2.0	15.5 ^b	79.1 ^b	NA	66.9	NA	NA	NA	466 ^b	518 ^b (111.2 ^b)	NA	NA
	RG (60 kg N/ha)	Control	0.0	15.6 ^c	80.9 ^c	NA	67.7	NA	NA	NA	584 ^c	472 ^c (80.8 ^c)	NA	NA
		Soybean meal	2.0	16.9 ^d	81.8 ^d	NA	66.3				706 ^d	570 ^d (80.7 ^c)	NA	NA
García et al., 2000 (Confinement) ⁶	WO	Control	0.0	7.0	81.5	59.4	72.7	3.2 ^a	60.0	71.5	320 ^a	162 (53.0 ^a)	59 (19.1)	102
		Barley	2.6	6.7	81.2	54.1	66.5	2.4 ^b	56.2	75.5	222 ^b	143 (61.7 ^b)	40 (18.3)	103
		Corn	2.4	7.5	81.6	54.6	66.9	2.8 ^b	60.1	84.4	273 ^b	159 (59.0 ^b)	64 (23.7)	94
Jones-Endsley et al., 1997	A/OG	12% CP	6.9	16.7 ^a	73.4 ^a	NA	NA	9.1 ^a	65.2 ^a	NA	587 ^a	446 ^a (75.9)	144 ^a (25.4)	302
		16% CP	7.0	18.2 ^b	75.7 ^b	NA	NA	10.1 ^b	68.1 ^b	NA	690 ^b	504 ^b (73.0)	187 ^b (27.4)	317
		6.4 kg/d	5.6	16.5 ^a	74.6 ^b	NA	NA	9.1 ^a	65.2 ^a	NA	620	461 (74.4)	157 ^a (26.4)	303
		9.6 kg/d	8.4	18.4 ^b	74.5 ^b	NA	NA	10.1 ^b	68.1 ^b	NA	656	489 (74.5)	174 ^b (26.3)	315
O'Mara et al., 1997	RG	Control	0.0	12.5	73.5	51.2	NA	NA	NA	NA	379	397 (108)	116 (35)	241
		Beet pulp	2.7	12.7	76.2	51.6	NA	NA	NA	NA	410	389 (119)	109 (34)	280
Van Vuuren et al., 1993 (Confinement) ⁶	RG	Control	1.7 ^a	14.6	78.6	59.4 ^a	75.6 ^a	6.61 ^a	78.7 ^{ab}	95.0 ^a	459 ^a	409 (89.1)	NA	254
		Starch	7.0 ^b	14.8	78.0	51.2 ^b	65.7 ^b	5.73 ^b	74.5 ^b	85.6 ^b	441 ^b	424 (96.1)	NA	261
		Fiber	7.2 ^b	14.8	78.9	60.6 ^a	76.7 ^a	6.72 ^c	79.2 ^a	93.8 ^a	428 ^c	396 (96.8)	NA	243

^{a,b,c,d}Means within reference with different superscripts differ ($P < 0.05$; unless otherwise stated: Berzaghi et al., 1996; Jones-Endsley et al., 1997; $P < 0.10$).

¹OMI = total organic matter intake; TTAD = total tract apparent digestibility; RAD = ruminal apparent digestibility (% of intake); RADD = ruminal apparent digestibility (% of total digested).

²NDFI = Total OM intake; TTAD = total tract apparent digestibility; RADD = ruminal apparent digestibility (% of total digested)

³NAN = Nonammonia N; NANMN = nonammonia nonmicrobial N; MN = microbial N.

⁴A = alfalfa (*Medicago sativa*); OG = orchardgrass (*Dactylis glomerata*); RG = perennial ryegrass (*Lolium perenne*); TF = tall fescue (*Festuca arundinacea*); WC = white clover (*Trifolium repens*); WO = winter oats (*Avena sativa*).

⁵Not available.

⁶In confinement studies, fresh cut-forage was used instead of grazed pasture.

but reduced milk fat percentage 6%. Supplementation with nonforage fiber sources or processed corn did not affect total DMI, milk production, or milk composition compared with dry corn. Replacing RDP sources for RUP sources in the concentrate did not affect milk production or composition. Forage supplementation did not affect production of grazing dairy cows when SR was high. Fat supplementation increased milk production by 6%, without affecting milk fat and protein content; however, none of those studies were conducted with cows producing more than 30 kg/d.

Compared with pasture-only diets, increasing the amount of concentrate in the diet reduced ruminal pH 0.08 and $\text{NH}_3\text{-N}$ concentration 6.59 mg/dl. The use of high moisture corn, steam-flaked or steam-rolled corn, barley, or fiber-based concentrates instead of dry corn did not affect ruminal pH or total VFA concentration, but reduced $\text{NH}_3\text{-N}$ concentration 4.36 mg/dl. Most of the studies showed that supplementation did not affect in situ pasture digestion, except for a reduction in rate of degradation when large amounts of concentrate were supplemented. Supplementation with energy concentrates did not affect digestibility of OM but reduced digestibility of NDF and intake of N without affecting the flows of NAN, NANMN, and microbial N. Protein supplementation increased digestibility of OM and NDF, and N intake and flows of NAN and NANMN without affecting the flow of microbial N.

ACKNOWLEDGMENTS

The authors thank Ignacio Ipharraguerre and Guillermo Schroeder for their comments and suggestions during the manuscript preparation.

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