AGRONOMIC STUDIES OF FORAGE BRASSICAS AS FULL-SEASON AND COVER CROPS FOR GRAZING IN NORTH DAKOTA

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Annual forages represent a good feed resource to extend the grazing season into fall and winter, providing a good quality forage for the livestock, allowing more efficient use of rangeland, and improving soil properties. Many species in the Brassicaceae family are used as forages for grazing. Forage brassicas have high forage yield, high nutritive value, low cost of establishment and harvest (direct grazing), and provide many ecosystems services. Forage brassicas can be grown as full season forage crops or as cover crops planted after a grain crop. The objectives of this study were: 1) to identify brassicas species and cultivars with high biomass production and forage quality when grown as full-season and as cover crops; 2) to determine their optimum sowing date, plant density and the response to different N and S fertilization rates. Replicated experiments were conducted at four sites Fargo, Prosper, Carrington and Walcott, ND in 2012-2014. Results indicate swede (*Brassica napus* L. var. *napobrassica*) and kale [*B.oleraceae* L. convar. *acephala* (DC)] were the highest forage yielding brassicas when established in full-season and turnip [*Brassica rapa* L. *var. rapa* (L.) Thell).], cv. 'Appin' was the highest yielding sown in August. In full-season brassicas, delaying sowing date reduced total forage yield but did not influence forage quality. In brassicas sown after August, total forage yield decreased significantly only in radish in the second sowing date. Plant density did not have an effect on forage yield averaged across environments and species in full-season forage brassicas. This was different in brassicas sown after August, where the highest forage yield was obtained with the highest plant density (≥200 plants m^{-2}). Kale and swede leaf and root/stem yield increased up to 200 kg N ha^{-1} in a linear response. Sulfur and the interaction between N and S did not have an effect in forage yield and quality. Both full-season and cover crops forage brassicas have great potential as supplemental high quality forage for grazing in North Dakota.

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DEDICATION

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CHAPTER 1. INTRODUCTION

Grassland and rangeland are widespread important ecosystems on the earth's surface (White et al., 2000), compromising about 40% of the terrestrial area (FAO, 2005). In the Great Plains of North America, these ecosystems support many livestock operations and several ecosystem services (Allred et al., 2014). Unfortunately, the area of these natural ecosystems has declined due to their conversion to cropland, with a net loss of 9.3 million ha only between 1982 and 1997 (Samson et al., 2004). North Dakota reported 5.1 million ha grassland in 2012 (USDA-NRCS, 2015), about 1.8 million cows and calves (*Bos taurus* L.) and 65,000 sheep/lambs (*Ovis aries* L.), plus other minor animal species (USDA-NASS, 2012).

In North Dakota, forages are the third most important crop with 1.05 million ha in total and 165,457 ha of alfalfa (*Medicago sativa* L.) in 2015 (FSA, 2015). Although, annual forages are not extensively grown in the state, annual cereals such as oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), and oat/pea (*Pisum sativum* L.) mixtures are grown as emergency forage, after winter-killed alfalfa or just to increase forage availability early in the season. Annual forages represent a good feed resource to extend the grazing season into fall and winter, providing a good quality forage for the livestock (Neville et al., 2010), allowing more efficient use of rangeland, and at the same time improving soil properties (Sedivec et al., 2013).

Forage brassicas are annual forages species cultivated for livestock production (Najda, 1991; Smith and Collins, 2003), grown in New Zealand, Australia, North America (Jung et al., 1986; Jacobs et al., 2001; Nichol et al., 2003; Wilson et al., 2006, Neilsen et al., 2008; Keogh et al., 2011), Europe (Neilsen et al., 2008), and northern Asia (Bilgili et al., 2003). In the USA, forage brassicas were introduced between the 19th and 20th centuries but then almost abandoned in the 1950's mainly due to lack of pest control methods and high production costs (Jung et al., 1984; Rao and Horn, 1986; Smith and Collins, 2003; McCartney et al., 2009).

Forage brassicas are characterized by high forage yield, with high nutritive value, low establishment and harvest cost (direct grazing), while providing many ecosystems services (Rao and Horn, 1986; Wiedenhoef and Barton, 1994; Ayres and Clements, 2002; Fulkerson, 2008; Neilsen et al, 2008; de Ruiter et al., 2009; Lemus, 2009; Rowe and Neilsen, 2010; Ward and Jacobs, 2013). Brassicas grow well with low temperature (0-5ºC) and they are tolerant to frost (-10ºC), extending the grazing season in the fall (McCartney et al., 2009; Ward and Jacobs, 2013). The extension of the grazing season reduces feeding costs, increasing the profitability of the operation (Penrose et al., 1996).

Brassicas have gained great importance as cover crops in cropping systems in the last decades, due to their many environmental and agronomic benefits (Weil and Kremen, 2007). Additionally, a cover crop can protect the soil during fallow periods, enhancing physical, chemical, and biological soil properties, affecting positively the next cash crop performance (Sainju et al., 2002; Fageria et al., 2005; Dagel et al., 2014).

Species in the Brassicaceae family (henceforth Brassicas) have been used as cover crops due to their fast growth in the fall and high biomass production (Chen et al., 2007; Geiske et al., 2016). Brassicas long, thick, and deep taproots can break the compacted soil layers, reducing subsoil compaction (Williams and Weil, 2004; Chen et al., 2007; Weil and Kremen 2007; Chen and Weil, 2011), increasing water infiltration (Dabney et al., 2001; Williams and Weil, 2004; Chen et al., 2007, Chen et al., 2014), and reducing soil erosion (Weil and Kremen, 2007; Stavi et al., 2012; Gruver et al., 2016). These species also can increase soil fertility remobilizing residual NO_3-N, P, and other nutrients from deep in the soil (2 m or more) to upper soil layers, becoming available for the next crop (Marschner et al., 2007; Chen et al., 2007; Dean and Weil, 2009; Liu et al., 2015; Gieske et al., 2016). Their deep root system allows them to extract water to 2-m depth with high water use efficiency (WUE), even higher than 30 kg DM ha^{-1} mm^{-1} (de Ruiter et al., 2009). Additionally, brassica cover crops have gained high interest to be used as biopesticides to control soilborne pests (Haramoto and Gallandt, 2005a; Chen et al., 2007; Ackroyd and Ngouajio, 2011; Bjorkman et al., 2015).

Determining the best management practices of brassicas used as forage and cover crops is necessary to obtain their benefits in cropping systems. These include species and cultivar selection, sowing rate, plant density, and nutrient requirements. Sowing rate is important for plant growth because this may influence plant architecture, height, leaf to stem ratio, and forage production (Stefanski et al., 2010). Each forage brassica species has different nutrient requirements, depending on soil fertility and the expected yield response (Wilson et al., 2006; de Ruiter et al., 2009). Brassicas, as forages or cover crops, production research in North Dakota is limited. Although a few new trials on forages brassicas grazing have been conducted with good results (Neville et al., 2007; 2010).

The general objective of this research was to determine the agronomic potential of several forage brassica species both as forage resource and as cover crops. The specific objectives of this study are: 1) to identify brassicas species and cultivars with high biomass production and high forage quality when grown as full-season and as cover crops in North Dakota; 2) to determine their optimum sowing date and optimum plant density to maximize their yield and quality, and 3) to determine their response to different N and S fertilization rates.

CHAPTER 2. LITERATURE REVIEW

2.1. Forages brassicas

Forage is defined as "edible parts of plants, other than separated grain, that provide feed for animals, or can be harvested for feeding" (Barnes and Nelson, 2003). Even though grasses (Poaceae) and legumes (Fabaceae) are the most important forage resources, some forbs have been gaining importance. Forage brassicas are the most important forbs used as forages in animal production.

2.1.1. Botanical classification and species

The Brassicaceae (former Cruciferae) family includes many different genera. The genus *Brassica* is the most economically important within this family, which include different species with multiples uses (Branca and Cartea, 2011). Six centuries ago, some species of brassicas were used for livestock feed (Najda, 1991; Smith and Collins, 2003). Species such as turnip [*Brassica rapa* L. *var. rapa* (L.) Thell).], swede or rutabaga (*B. napus* L. var. *napobrassica*), forage rape (*B.napus* L.), kale [*B. oleracea* L. convar *acephala* (DC)] (Ayres and Clements 2002; McCartney et al., 2009; Gowers, 2010; Westwood and Mulcock, 2012), and some hybrids like *B. rapa* L. x *B. pekinensis* L. (Wiedenhoef and Barton, 1994) or *B. rapa* L. x *B. oleracea* L. (Frischke, 2011) have been widely used as a forage crops. Also, canola or rapeseed (*B. napus* L.) which is an oilseed, has foliage can be used as forage for grazing (MAFRI, 2004; Schroeder, 2008). In the last decades, some of these species, such as turnip, rape, and some hybrids, have become important cover crops.

Forage radish (*Raphanus sativus* L.) is widely used as cover crops in the USA but also has been reported as an excellent forage in Canada due to their high biomass yield and quick regrowth allowing several grazing events (McCartney et al., 2009). Ethiopian cabbage or

Ethiopian mustard (*B. carinata* L.), has the potential to be used both as cover crop, companion crop or forage (Hunter and Roth, 2010).

2.1.2. History and distribution of forage brassicas

Forage brassicas have been produced and used in different areas of the world, especially in Australia, New Zealand, and North America (Jung et al., 1986; Jacobs et al., 2001; Nichol et al., 2003; Wilson et al., 2006, Neilsen et al., 2008; Keogh et al., 2011). Also, historically these species have been utilized in Europe for more than six centuries, especially to feed sheep (Najda, 1991). In the USA, brassica forage crops were introduced by European immigrants (Jung et al., 1983) and have been studied as forage crops in humid zones of the USA and Canada (Jung et al., 1984). These species were commonly used in the last part of the 19th century and the beginning of the 20th century (Jung et al., 1984; Smith and Collins, 2003). The use of forage brassicas began to decline since 1950's due to high cost to produce them (Jung et al., 1984; Smith and Collins, 2003), high labor requirement, and diseases, and insect problems (Rao and Horn, 1986). However, in the last decades, these forage crops had a comeback, as full-season forage crops for grazing and also as cover crops. The recent developments in forage production technology and plant breeding have stimulated renewed interest on brassicas as potential forage crops for livestock (Rao and Horn, 1986). In New Zealand, forage brassicas are the most important annual forage used for milk and beef production (Salmon and Dumbleton, 2006; de Ruiter et al, 2009). Also, some forage brassicas have wider geographical distribution than others. Forage turnip is widely grown in northern Europe, and is also distributed over much of northern Asia, northern North America, and southern Oceania (Bilgili et al., 2003). Turnip has been an important annual forage for livestock production in Europe, New Zealand, North America, and Australia (Neilsen et al., 2008). Swedes are the third most important vegetable crop in Scotland (Gowers, 2010), and the second most grown forage brassica after turnips in New Zealand (Chakwizira et al., 2011).

2.1.3. Characteristics of brassicas as forage

Brassicas have several desirable characteristics that make them useful as forages. Most researchers working with forage brassicas agree that the most important characteristics are: i) abundant forage at the time when most warm- and cool-season grasses are not productive (winter), ii) higher forage yield and quality (energy, protein, digestibility, and minerals), iii) low establishment and harvest cost when using direct grazing, and iv) added environmental benefits when in crop rotations (Rao and Horn, 1986; Ayres and Clements, 2002; Fulkerson, 2008; Neilsen et al., 2008; de Ruiter et al., 2009; Lemus, 2009; Rowe and Neilsen, 2010, Undersander, 2013).

2.1.3.1. Phenology

The most representative forage brassicas have biennial growth cycle (turnip, rape, kale, swede and hybrids), but in livestock systems they are grown as annuals (Hall and Jung, 2008, Lemus, 2009). They grow vegetatively in the first season (storing yield in roots or stems) and produce seed in the second season (de Ruiter et al., 2009). However, in areas with harsh winters many forage brassicas grow as annuals because they get winter-killed (Stewart, 2002). Knowing growth staging is useful in crop protection, in plant breeding and other disciplines where a proper definition of crop growth stages is essential (Theunissen and Sins, 1984). Developmental growth staging for brassicas was developed by Harper and Berkenkamp (1975) and Theunissen and Sins (1984). The first three stages are similar for all brassicas species. Stage zero (0) is a pre-emergence or seed stage. Stage 1 (1), seedling stage, starts with the germination of the seed, the elongation of the hypocotyl, and ends with the unfolding of the two cotyledons. Stage 2 (2), rosette stage, starts with both cotyledons fully extended and ends with the first two true leaves fully expanded. At stage 3 (3), harvest or grazing stage, the internodes elongate, the plant increases in height, and growth rate is the fastest. The axillary buds become visible and the growth slows down gradually at the end of stage 3 (Harper and Berkenkamp, 1975; Theunissen and Sins, 1984).

In some species, the above ground biomass is mostly leaves and stems (kale, canola, forage rape, and some hybrids), others have part of the above ground biomass as enlarged hypocotyls (turnip and swede) or roots (radish) (Lemus and White, 2014). Both will be referred as 'roots' henceforth.

2.1.3.2. Physiology

Growing degree days (GDD) to maturity has a major effect on forage brassicas biomass yield potential (de Ruiter et al., 2009). A base temperature of 0°C has been used by some authors to calculate the GDD for brassicas (Darby et al., 2013; Björman et al., 2015). Other plants belonging to this family such as white or yellow mustard (*Sinapis alba* L. and brown or oriental mustard *Brassica juncea* (L.) Czern.), can accumulate biomass as long as the temperature is above freezing (Björkman et al., 2015). However, de Ruiter et al. (2009) mentioned that thermal time above 4°C determines the rate of leaf appearance.

Brassicas are cold-hardy (Jost, 1998), and can tolerate freezing temperatures in the winter (Jung et al., 1983; Jung et al., 1986; Smith and Collins, 2003; Keogh et al., 2011). The ability to grow at temperatures near 0ºC gives them an advantage over most grasses and legumes during the winter (Smith and Collins, 2003). Brassicas, in general, can tolerate temperatures down to -5°C (Najda, 1991). Different species of brassicas have different winter hardiness which varies with cultivars and organs of the plant (Villalobos and Brummer, 2013). Turnip leaf can generally survive temperatures between -6 and -10°C. Turnip root can tolerate temperatures of -13°C (Bartholomew and Underwood, 1992; Penrose et al., 1996; McCartney et al., 2009). Turnip can survive temperature of -9.4°C (Lemus and White, 2014), and they require several days below freezing to be killed (Rook, 1998; Jost, 1998). Kale is the most cold tolerant forage brassica surviving -12°C (Jost, 1998; Lemus, 2009; Lemus and White, 2014). However, Penrose et al. (1996) determined that kale cv. Premier survived an entire winter, with a minimum temperature of -22°C air temperature. Turnip, swede, and hybrid cultivars evaluated in the same location and season survived temperatures of -11°C at the end of November, but they froze at -22°C (Penrose et al., 1996). Jung et al. (1986) observed that swede root cv. Calder remained alive in the 1981-1982 winter, whereas all other root crops were dead by mid-winter. That winter, the minimum air and soil (5-cm depth) temperature were -28°C and -17°C, respectively.

Conversely, forage brassicas also are tolerant to heat. High dry matter production with temperatures of about 32°C have been reported (Smith and Collins, 2003). This temperature was used by Darby et al. (2013) to determine the maximum temperature for GDD calculations. Forage brassicas accumulate about 1.1 Mg dry matter (DM) ha^{-1} per each 100 GDD, base temperature 0˚C and maximum temperature 32˚C, without soil water constraints nor fertility (de Ruiter et al., 2009).

Brassicas species used as cover crops are fast-growing, cool-season annuals with some frost tolerance as well (Chen et al., 2007). Forage radish is sensitive to frost and winter-kills with prolonged exposure to temperatures below -4°C (Weil et al., 2009). In the Mid-Atlantic, forage radish leaves are first damaged by frost in late November or early December but shoots can resume growth. The growing point is often protected by surrounding foliage, until it is finally killed by temperatures below -4°C in January or February (Lawley et al., 2012).

2.1.4. Forage brassica biomass production

Most forage brassicas reach their maximum biomass yield between 80 to 150 days after planting (DAP) (Tiryakioglu and Turk, 2012). Turnip is a short-season, fast-growing annual crop, which requires 80 to 100 DAP to achieve maximum dry matter production (Jung et al., 1983; Smith and Collins, 2003; Albayrak et al., 2004; Lemus, 2009; Jacobs and Ward, 2011; Lemus and White, 2014). Swede has a longer vegetative period than turnip and grows slower requiring 120 to 180 DAP to achieve maximum biomass production (Jung et al., 1983; Wiedenhoef and Barton 1994; Lemus, 2009; Lemus and White, 2014, Benedict et al., 2013). Narrow-stem kale is more productive than the other brassicas and require as much as 120 to 180 DAP to accumulate maximum biomass (Wiedenhoef and Barton, 1994; Jung et al., 1986; Jung et al., 1983). However, depending on the type of kale the growth period can be much shorter. Stemless kale cultivars require only 90 DAP for maximum yield, allowing a second harvest (Hall and Jung, 2008; Lemus, 2009; Lemus and White, 2014). Forage rape and hybrids need about 120 DAP to accumulate maximum biomass, although some maximize biomass at 82 DAP. Most cultivars are ready for grazing at 60 DAP, but need 30 additional days of regrowth for a second grazing (Wiedenhoef and Barton, 1994; Jung et al., 1983; Lemus 2009; Lemus and White, 2014; Judson et al., 2013). Kale hybrid cv. 'Winfred' can also be used for winter grazing and is ready for grazing about 75 DAP in the fall (Frischke, 2011).

The biomass production of forage brassicas differs depending on the species, cultivar, management, and environmental conditions. Maximum biomass yield is achieved at physiological maturity (PM), when the basal leaves begin to senesce and the tops change in color (Ayres and Clements, 2002).

Forage brassicas biomass yield fluctuates between 4 and 12 Mg dry matter (DM) ha^{-1} in 5 to 6 months after planting, depending on species (Keogh et al., 2011). Swede and kale, generally have higher forage yield than other forage brassicas, because of their longer vegetative period. Forage yield fluctuates between 15 and 20 Mg DM ha^{-1} under optimal environmental and management conditions (Wilson et al., 2006; Brown et al. 2007; Fletcher et al. 2007, Fletcher et al, 2010; Gowers et al., 2006; de Ruiter et al., 2009). Under irrigation and high N fertilization rates, kale was reported to achieve 25 Mg DM ha^{-1} of high quality forage (Chakwizira et al., 2015b).

Forage yield increased from 4 to 11 Mg DM ha^{-1} in swede and from 2.5 to14 Mg DM ha^{-1} in kale, harvesting at 60, 90, 120, and 150 DAP (Jung et al., 1986). Likewise, in Canada, swede forage yield increased from 7.4 to 9.4 Mg DM ha^{-1} when the harvest was delayed from 16 September to 6 December (Kunelius et al., 1989). In a survey of 49 commercial kale cultivars in New Zealand, the DM yield averaged 10.9 Mg DM ha^{-1} and varied from 5.3 to 17.0 Mg DM ha^{-1}. Kale type had a significant effect on total forage yield with the intermediate-stem type averaging 9.9 Mg DM ha^{-1} and giant types 13.6 Mg DM ha^{-1}. Cultivar, fertility, sowing date and in-crop moisture were all factors that contributed to forage yield variation (Judson et al., 2010). Turnip can easily produce about 5 Mg DM ha^{-1}, however, in fertile soil and with even rainfall distribution and temperatures below 25°C, they can yield 8 Mg DM ha^{-1} or more. Turnip biomass yield between 5.9 and 8.1 Mg DM ha^{-1} were reported in Ohio (Penrose et al., 1996), while similar yields were reported by Jung et al. (1986) 60 to 90 DAP, respectively. Other researchers have reported biomass yield average between 4 and 8 Mg DM ha^{-1} (Rao and Horn, 1986; Jung et al., 1983; Kalmbacher et al., 1982). The lowest biomass yield reported is 1.2 Mg DM ha^{-1} (Griffin et al., 1984). In North Dakota, a trial conducted at Carrington in 2003, with four turnip cultivars had an average forage yield of 6.1 Mg DM ha^{-1} (NDSU, 2003). Although, much lower biomass turnip yields were reported by Neville et al. (2007), in Streeter, ND. Forage rape usually has less biomass than kale, but under adequate conditions (management and environment), yield can be 10 Mg DM ha^{-1} or more. Biomass yield fluctuates with harvest date, ranging between 4 and 7 Mg DM ha^{-1} harvested at 60 to150 DAP, but depending on the country and harvest dates biomass yield can vary between 7.6 to 10.2 Mg DM ha^{-1} (Garcia et al., 2008; Fletcher and Chakwizira 2012b; Judson et al., 2013). In a trial conducted at Carrington, ND, in 2003, the average forage yield of three cultivars of rape was 3.5 Mg DM ha^{-1} (NDSU, 2003). Hybrid forage brassicas had high yield fluctuation depending of the species. Penrose et al. (1996), reported a yield of 6.1 Mg DM ha^{-1} with the hybrid Tyfon, while Griffin et al. (1984) reported 6.7 Mg DM ha^{-1} with the same hybrid. Conversely, 'Winfred' biomass yield was 13.8 Mg DM ha^{-1} with above-normal rainfall, but with below-normal rainfall yield was only 3.5 Mg DM ha^{-1} (Ward and Jacobs, 2013). Winter canola also has been used as a double crop for winter grazing and seed (Dove et al., 2012).

2.1.5. Forage brassicas management

2.1.5.1. Field selection and soil preparation

Brassicas can be grown in different kind of soils. Soil depth of 1 m or more is ideal for root development and water uptake (de Ruiter et al., 2009). Brassicas perform better on well drained soils, without waterlogging problems (Jung et al., 1983; de Ruiter et al., 2009; Keogh et al., 2011). Additionally, forages brassicas should be integrated in a crop sequence or rotation, to manage soil fertility, and weed and pest control (de Ruiter et al, 2009). The soil preparation must provide a firm seed bed in conventional tillage system (de Ruiter et al., 2009). No till or direct drilling has been used but the results have varied (Ayres and Clements, 2002). If no till is chosen, higher amount of N should be applied to compensate the lower N mineralization (de Ruiter et al., 2009).

2.1.5.2. Sowing date and sowing depth

Emergence and establishment of forage brassicas depends on soil water content and temperature at the time of sowing. Available water content in the soil and warmer temperatures in a fall sowing resulted in early emergence and establishment, whereas spring emergence and seedling growth was delayed due to lower than optimum temperatures (Rao and Horn, 1996; Jung et al., 1983; Keogh et al, 2011). Brassica species germinate over a wide range of temperatures, but the optimum range is from 10 to 35°C (Smith and Collins, 2003). At these temperatures, the emergence may occur between 4 to 5 days. Under favorable conditions forage rape germinates rapidly (2-4 days) in late summer and early autumn (Fulkerson, 2008). Jung et al. (1986), using conservation tillage, determined that seed germination was 26% at 15°C and 80% at 21°C six DAP. With soil temperature less than 12°C, seedling emergence occurred 10 DAP.

The optimum sowing date depends on final crop use, brassica species, management, and environment. For summer grazing, most of the species must be planted early in spring (March/April), to use soil water and catch enough spring rainfall (Ayres and Clements, 2002). Early sowing dates increase total GDD improving potential forage yield.

Studies have indicated that weed competition is a major problem in brassicas establishment (Griffin et al., 1984). For that reason, sowing when soil temperature is optimum will allow faster germination and emergence. Studies conducted in the 1970's, determined that delaying the sowing date reduced forage yield of kale (Fulkerson and Tosell, 1972). End of May sowing resulted in higher DM yield of kale and swede than sowing on 16 June or 14 July (Dibb and Brown, 1964). In the Atlantic region of Canada, forage rape, radish, and hybrid turnip forage yield did not differ when established in May, June, or July. However, kale yield declined when sown after June (Kunelius et al., 1987). Additionally, sowing and harvest dates affected length and diameter of turnip roots. The largest roots were obtained sowing in 20 June compared with 5 July and 20 July (Tiryakioglu and Turk, 2012). Also, Sprague et al. (2014) working with winter canola for grazing, determined that early sowing dates generated more biomass yield than those sown later. Forage brassicas quickly decline in forage yield as fall sowing is delayed from 1 August to 31 August, in Ireland. In this study, biomass yield decreased in 74.5% in forage rape, and in 55.5% in turnip (Keogh et al., 2011).

Brassica seeds are very small, thus to obtain maximum germination and good stand establishment, the sowing depth must be shallow (Ayres and Clements, 2002). 'Barkant' turnip sown at a depth of 10 mm emerged faster in 7 DAP, than at greater depths. However, 15 DAP emergence rates were similar between 10- and 25-mm depths. Lowest total emergence was observed at 0- (surface) and 50-mm depths (Salmon and Dumbleton, 2006). Recommended sowing depth ranges between 6.3 and 12.7 mm in soils with fine texture and between 12.7 and 19 mm in coarse-textured soils (Smith and Collins, 2003; Lemus and White, 2014; Ayres and Clements, 2002; de Ruiter et al., 2009).

2.1.5.3. Sowing rate and plant density

Sowing rate is important for plant growth because it may influence plant architecture, height, and leaf to stem ratio (Stefanski et al., 2010). Also, differences in plant architecture may produce overgrazing of the growing point decreasing energy reserves and affecting plant regrowth. Sowing rates between 2 and 5 kg ha^{-1} changed the consumption preference by the animals and the utilization of the crop, without changing the forage quality of rape. Forage utilization decreased when the density increased (Stefanski et al., 2010). Cho et al. (1998) determined that the stem diameter decreased from 2.1 to 1.8 cm, and the leaf/stem ratio decreased from 31.2 to 22.9%, when forage rape sowing rate was increased from 3 to 15 kg ha^{-1}. Recommended sowing rates vary between 3.4 and 5.0 kg ha^{-1} for forage rape and kale and between 0.8 and 4.5 kg ha^{-1} for turnip and swede depending on the country and cultivar (Smith and Collins, 2003; Lemus, 2009; Lemus and White, 2014; Smart et al. 2004; Ayres and Clements 2002; de Ruiter et al., 2009). However, Cho et al. (1998), determined that the optimum sowing rate for forage rape 'Sparta' was 11 kg ha^{-1} which yielded 22.0 Mg DM ha^{-1}.

In forage rape, plant density was 45% lower with 2 kg ha^{-1} than 5 kg ha^{-1} (Stefanski et al., 2010). With low sowing rates, as the area available for plant growth increases, plant diameter also increases. High plant density limits nutrient uptake and photosynthetic activity, reducing translocation of nutrients to roots and leaves (Albayrak et al., 2004). Additionally, high sowing rates in turnip and swede will likely result in smaller roots which pose the risk of chocking cattle (Smith and Collins, 2003). Also, lower sowing rates may reduce waste during grazing as the apical growing point remains near the soil surface (Stefanski et al., 2010). Thus, cattle can graze to a lower residual level without removing the apical growing point and setting back regrowth. This will likely result in greater forage utilization, because plants are well spaced, minimizing waste by trampling. Conversely, higher sowing rates produce thinner stems and proportionally more leaf material, with higher protein content (Stefanski et al., 2010). Albayrak et al. (2004) determined that turnip root yield and weight increased when row spacing was increased. At 40-cm row spacing root and leaf yield was greater than at 20-, 30-, and 50-cm row spacing. The average turnip forage yield was 2.8, 4.5, 5.3, and 4.7 Mg DM ha^{-1} at 20-, 30-, 40-, and 50-cm row spacing, respectively. Root diameter and length was greater at 50-cm row spacing. Leaf yield was greater at 40-cm row spacing.

2.1.5.4. Fertilization response

Each forage brassica species has different nutrient requirements, depending on soil fertility, intended use, and the expected yield response (Wilson et al., 2006; de Ruiter et al., 2009). The amount of fertilizer to maximize forage yield depends on the difference between crop nutrient demand and nutrient supply from the soil (de Ruiter et al., 2009). Management of soil and fertilization are key to profitable and sustainable crop production (Chakwizira et al., 2011; Fletcher and Chakwizira, 2012a). Nutrient supply needs to be closely matched to crop demand. Sub-optimal nutrient supply will result in lower yield, while excess nutrient application can lead to leaching and run-off of nutrients and potentially create nitrate toxicity to animals (Chakwizira et al., 2011). Grazing of forage kale can cause ground water pollution through nitrate leaching. To minimize N loading, N fertilization must match crop requirements (Chakwizira et al., 2015b).

The most important nutrients for forage brassicas are N, P, S, K, Mo, and B. Soil testing for nutrients such as Mg, Cu, and Co (Aymes and Clemets, 2002; de Ruiter et al., 2009) and Ca, Zn, Fe, and Mn might be necessary in certain locations (Guillard and Allinson, 1989).

According to Smith and Collins (2003), brassica production is highly dependent on available soil N. Nitrogen is required in large amounts in plant tissue, as a component of plant proteins, amino acids, nucleotides, nucleic acids, and chlorophyll (Grant and Bailey, 1993). Nitrogen application influences mainly crude protein (CP) content in forages, but also affects metabolizable energy (ME), neutral detergent fiber (NDF), and starch content of turnip roots

(Jacobs and Ward, 2011). Nitrogen is needed in higher quantity in forage brassicas than grasses, because of their higher CP content (Smith and Collins, 2003).

Leafy brassica species require large amounts of N, hence, N fertilizers are the most important production input (Keogh et al., 2011). Nitrogen is applied to increase forage yield, but the response depends on soil N and yield potential (Fletcher et al., 2012a; Chakwizira et al., 2011; Keogh et al., 2011; Fletcher and Chakwizira, 2012b). The N requirement in most brassica crops in New Zealand ranges from 250 to 500 kg N ha^{-1}. They respond strongly to N fertilization if the soil has less than 150 kg available N ha^{-1} (available N tested at 15 cm of soil depth, according with Keeney and Bremmer (1966) procedure) (de Ruiter et al., 2009). Forage kale Naccumulation was 22 kg N Mg^{-1} DM with 12 Mg DM ha^{-1} of biomass (Judson et al., 2010) and only 20 kg N Mg^{-1} DM when total biomass production was 18 Mg DM ha^{-1} (Wilson et al., 2006). The total N accumulation differed with N application (Fletcher and Chakwizira, 2012b). In a rain-fed condition and no N application, kale took up 13.5 kg N Mg^{-1} DM, but when fertilized with 300 kg N ha^{-1} the N accumulation increased to 32.7 kg N Mg^{-1} DM (Chakwizira et al., 2015b). Jacobs et al. (2006) reported that application of N fertilizer from 150 to 300 kg N ha^{-1} increased forage rape yield from 9.8 to 13.6 Mg DM ha^{-1}. Chakwizira et al. (2011), determined a yield increase from 7.0 Mg DM ha^{-1} with 0 kg N ha^{-1} to 9.7 and 10.5 Mg DM ha^{-1} with 120 to 300 kg N ha^{-1}, respectively. These recommended N rates are similar to the 140 kg N ha^{-1} recommended for forage swede in Otago, New Zealand (Stevens and Carruthers, 2008).

Application of N fertilizer can lead to an accumulation of nitrate (NO_3-N) in forage brassicas, particularly when N application rates exceed the requirement (Fletcher and Chakwizira, 2012b). This may result in potentially toxic NO_3-N (antinutritional compounds) content in grazeable plant tissues, leading to animal health issues and/or environmental pollution (Chakwizira et al., 2015b). Forage kale and rape, generally have higher NO_3-N concentration than turnip and swede. This is because roots, the major yield component of turnip and swede, have lower NO_3-N content than stems, which make up the bulk of yield in kale and rape (Fletcher and Chakwizira, 2012b). Additionally, Chakwizira et al. (2015a) reported that NO_3-N contents were higher in kale stems and petioles (which included the midrib of the leaf) than in leaves. Nitrate concentration was highest at the bottom of the kale stem and decreased towards the top. Also, NO_3-N content on the whole-plant (kale and rape) increased with N supply, and long periods of low rainfall in the summer (Chakwizira et al., 2015a). Rape and kale had nearly double of NO_3-N content compared with turnip and swedes (5.5 mg g^{-1} DM and 2.9 mg g^{-1} DM, respectively). Chakwizira et al. (2015a) determined that the NO_3-N content increased from 0.1 mg g^{-1} to 2.3 mg g^{-1} from 0 to 500 kg N ha^{-1} in kale and 1.0 to 3.4 mg g^{-1} from 0 to 200 kg N ha^{-1} in forage rape. Fletcher and Chakwizira (2012b) recommended early application of N fertilizer to minimize NO_3-N accumulation in forage brassicas.

Aymes and Clements (2002) recommended to apply only 20 kg N ha^{-1} at sowing, broadcasting the remaining rate 2 or 4 weeks after crop emergence. Nitrogen split-applications can have some advantages (Widdowson et al., 1960), such as early biomass production for grazing (Sprague et al., 2014). However, Pelletier et al. (1976) determined that forage brassicas had higher CP with full application of N at sowing than with split-application. In New Zealand, the recommendation is to split N fertilizer into two applications, 6 and 12 weeks after sowing (WAS) in forage kale and 4 and 8 WAS in forage rape. This limits NO_3-N accumulation in the soil and the risk of leaching losses during the season. Late N applications almost doubled NO_3-N content in the plant tissue compared with early applications (Fletcher and Chakwizira, 2012b).

Where there is adequate soil water content, N application can improve forage yield and CP content in most summer forages (Jacobs and Ward, 2011). However, studies on N fertilization in turnip and other forage brassica species have indicated that under dryland conditions, forage yield response is variable (Jacobs and Ward, 2011).

Sulfur is the fourth major nutrient in crop production, ranked immediately behind N, P, and K in importance to crop productivity (Jamal et al., 2010; Piri et al., 2012). Although S is one of the essential nutrients for plant growth, this element has received little attention for many years because fertilizers and atmospheric SO_2 and H_2S inputs supplied the soil with adequate amounts of S for many years (Jamal et al., 2010; Aghajanzadeh et al., 2015). Industrial burning of high-S content coal released high amount of S-compounds to the atmosphere, however new regulations to reduce greenhouse gases emissions (GHG) and acidifying compounds reduced the S input to soils from the atmosphere (Aghajanzadeh et al., 2015).

Some crops require as much S as P, especially brassicas species (Grant and Bailey, 1993; Manaf and Ul-Hassan, 2006; Chen et al., 2007; Piri et al., 2012). However, S fertilization has erratic results. Forage brassicas respond strongly to N fertilizer but seldom to S (Wilson et al., 2006; Fletcher et al., 2010). Nitrogen and S requirements of crops are closely related because both nutrients are required for S-containing aminoacids (cysteine and methionine), protein synthesis, and various other cellular components, including thiol and secondary S-containing compounds, which have a significant role on protection of plants against stress and pests (Grant and Bailey, 1993; Piri et al., 2012; Anjum et al., 2011). Sulfur is contained in the biologically active compounds biotin, glutathione, thiamine, and coenzyme A, playing an important role in energy transfer and protein structure. This nutrient is involved in the synthesis of chlorophyll and is also required in plants of the Brassicaceae family for the synthesis of volatile oils, accumulating as glucosinolates (Grant and Bailey, 1993).

In general, N/S ratios from 4:1 to 8:1 are ideal for brassicas. A 7:1 N/S ratio in the soil is required for optimum growth of rape (Janzen and Bettany, 1984; Chen et al., 2007). However, Janzen and Bettany (1984) indicated that ratios below 7:1 reduced seed yield. Fazili et al. (2008) reported that S deficiency limits the N use efficiency, therefore, S addition becomes necessary to achieve maximum N use efficiency from applied fertilizer. An example of S and N interaction was reported by Fazili et al. (2008), in this study rapeseed and brown mustard (*B. juncea* L.) had S accumulation of 27 to 31% of the added S with no N fertilization and 37 to 38% when 60 kg N ha^{-1} was applied. Wilson et al. (2006) reported that kale's S extraction was 100 kg S ha^{-1} while application of 45 kg S ha^{-1} recorded significantly higher forage yield than 30 kg S ha^{-1} in forage rape (Piri et al., 2012).

The desirable method and timing of S fertilization depends on whether the fertilizer contains SO_4-S which is available to the plant or elemental S which must be oxidized before it becomes available to the plant. Sulfate-containing fertilizers are water soluble and leach easily (Grant and Bailey, 1993). Fertilizers containing SO_4-S should be preferred to those with elemental S which is released slower and causes soil acidification (Ayres and Clements, 2002). In soils with sufficient soil water for crop planting, spring broadcast or broadcast-incorporated application of SO_4-S is recommended. In soils with lower than average soil water content, side banding or presowing banding may be superior, because bands will be less subject to drying than the soil surface. In coarse-textured soils, leaching losses of SO_4^{2-} may occur during heavy rains (Grant and Bailey, 1993).

Phosphorus is an essential element that plays a key role in plant growth and metabolism and it is the major limiting nutrient for plant growth after N (Afshar et al., 2012). Phosphorus availability is associated with root development and hence crop establishment. The plant responds to P fertilization by either diverting resources to root production or increasing root proliferation in the high P regions with subsequent yield increase. A larger root volume will result in improved nutrient and water uptake (Chakwizira et al., 2011).

Forage brassica biomass yield responds strongly to P fertilization particularly where soil P is less than 15 mg kg^{-1} soil (White et al., 1999). For example, a 12 Mg DM ha^{-1} of kale biomass contained 34 kg P ha^{-1} (Judson et al., 2010) and 18 Mg ha^{-1} of kale contained 50 kg P ha^{-1} (Wilson et al., 2006). General recommendations for maximum forage yield of brassicas fluctuate between 25 to 50 kg P_2O_5 ha^{-1} rates (Wilson et al., 2006; Chakwizira et al., 2010; Chakwizira et al., 2011). Lemus (2009) recommended that kale should be fertilized with 100 to 112 kg P_2O_5 ha^{-1}, forage rape with 50 to 78 P_2O_5 ha^{-1}, and swede/turnip with 95 to123 P_2O_5 ha^{-1}. Banded P fertilizer (as opposed to broadcast) and applied at planting time may increase availability of P early in the season allowing the plants to establish a more effective root system early in the season and thereby increasing water use efficiency (Ayres and Clements, 2002; Lemus, 2009; Chakwizira et al., 2011).

Potassium is an activator of a number of enzymes, most notably those involved in photosynthesis and respiration. Potassium serves an important function in regulating the osmotic potential of cells and it is a principal factor in opening and closure of stomatal guard cells, and phototropisms (Hopkins and Huner, 2008).

Although not common, K deficiency can be corrected by adding a potash fertilizer (Ayres and Clements, 2002). Potassium requirement is high in all brassica forages (Smith and Collins, 2003). Fulkerson et al. (2008) reported that 8 Mg DM ha^{-1} of brassica biomass can uptake 144 kg K ha^{-1}, and the recommended fertilization should be 150 kg K_2O ha^{-1}. Lemus (2009) recommended kale should be fertilized with 100 to 112 kg K_2O ha^{-1}, forage rape with 50 to 78 K_2O ha^{-1}, and swede/turnip with 95 to 123 K_2O ha^{-1}.

The requirements of micronutrients in forage brassicas are not substantially different from those of other forage species (Smith and Collins, 2003). Molybdenum deficiency is common in acidic soils (pH < 5.5). It can be applied as Mo superphosphate or could be applied with seed treatment (Fulkerson et al. 2008). Additionally, liming to increase soil pH may also overcome Mo deficiency (Ayres and Clements, 2002; Fulkerson et al., 2008). Boron deficiency is relatively rare, but has been detected in recently limed soils or high pH alkaline soils. The deficiency can be overcome applying boron fertilizer in rates of 2 kg ha^{-1} (Ayres and Clements, 2002).

2.1.5.5. Other managements

Water availability is the main environmental source of forage yield variation in brassica forages (de Ruiter et al., 2009). Irrigation increases turnip biomass yield substantially, and water deficits during the growing season reduce forage yield (Rowe and Neilsen, 2010). Swede needs 38 mm H_2O wk^{-1} during the season to maximize root yield (Benedict et al., 2013). Kale and rape have more vigorous root systems than swede and turnip, and therefore they can utilize stored water more efficiently (de Ruiter et al., 2009). Eckard et al. (2001) reported that irrigation increased yields in turnip from 7.9 to 13.5 Mg DM ha^{-1} while similarly, Neilsen et al. (2000) reported increases from 6.1 to 12.6 Mg DM ha^{-1}. Other researchers also have reported that biomass yield nearly doubles with irrigation (Rowe and Neilsen, 2010).

Weeds, pests, and diseases can be problematic in brassicas but their presence vary with year and location (de Ruiter et al., 2009). Application of glyphosate (N-(phosphonemethyl) glycine) right before planting is a good option to control weeds (de Ruiter et al., 2009). Brassicas can quickly become dense enough to prevent germination of weed seeds (Ayres and Clements, 2002). However, seedlings are not good competitors with many annual weeds during the first few weeks, especially in spring and mid-summer establishments (Smith and Collins, 2003; de Ruiter et al., 2009). Pre-emergence herbicides can be used to minimize weed competition in early planting dates. Some post-emergence herbicides are available to control many broadleaf and grass weeds (de Ruiter et al., 2009). Once established, brassica seedlings are more competitive (Ayres and Clements, 2002). Weed seeds emergence and competition is minimal in late planting dates (Smith and Collins, 2003).

Crop failure is often caused by insects or diseases on emerging or newly established seedlings. Seedlings of kale, turnip, and forage rape are especially susceptible to cabbage flea beetle (*Phyllotreta cruciferae* Goeze), and striped flea beetle (*Phyllotreta striolata* Fab.) (Smith and Collins, 2003; Benedict et al., 2012). Flea beetles feed exclusively on brassicas cotyledons and first true leaf, causing extensive damage (Benedict et al., 2012). In addition, cabbage moth (*Mamestra brassica* L.), cabbage butterfly (*Pieris rapae* L.), armyworm (*Spodoptera* sp.), and cabbage root maggot (*Delia radicum* L.) are commonly found in forage brassicas foliage (Smith and Collins, 2003). Some species of aphids (*Aphis brassicae* L. and *Lipaphis erysimi* Kaltenbach) also can cause problems (Benedict et al., 2012).

Diseases can be caused by fungal, bacterial, or viral pathogens (Ayres and Clements, 2002). The most important diseases include bacterial soft rot (*Erwinia carotovora* L.R. Jones), which affects the roots of mature turnip and swede, leaf spot associated with both *Xanthomonas* *campestris* (Pammel) Dowson, *Alternaria* sp., and *Cercospora* sp., and powdery mildew (*Erysiphe cruciferarum* Opiz ex Junell) (Smith and Collins, 2003). In addition, club root (*Plasmodiophora brassicae* Woronin) is a serious soil-borne disease of most brassicas worldwide (Benedict et al., 2013). Crop rotation avoiding repeat brassicas in the same field for 4 or 5 years reduces the risk of soil-borne diseases (Benedict et al., 2012 and 2013).

2.2. Cover Crops

Cover crops have been defined as "close-growing crop that provides soil protection, seedling protection, and soil improvement between periods of normal cash crops production, or between trees or vines in orchards and vineyards" (SSSA, 2008). Cover crops provide many environmental and agronomic benefits (Weil and Kremen, 2007), such as soil coverage during fallow periods, before crop establishment in spring or after crops are harvested in the fall. Additionally, cover crops can improve the performance and production of following crops due to enhancement of soil physical, chemical, and biological properties (Fageria et al., 2005). According to Carter (2002), the main objective to use cover crops is to enhance soil properties and the productivity of the subsequent crops.

2.2.1. Benefits of cover crops

Cover crops improve N economy (Fageria et al., 2005), increase soil organic matter content and carbon sequestration (Sainju et al., 2002; Dabney et al.,2001; Fageria et al., 2005), enhance soil fertility, reduce nutrient losses (Meisinger et al., 1991; Sainju et al., 2002; Vos and Van Der Putten, 2004; Fageria et al., 2005; Cupina et al., 2011; Dagel et al., 2014), improve soil structure, alleviate subsoil compaction (Williams and Weil, 2004; Fageria et al., 2005), reduce soil erosion, increase soil biological activity, conserve soil water (Fageria et al., 2005), suppress weeds, decrease disease and insect problems (Fisk et al., 2001; Fageria et al., 2005), and improve yield of subsequent crops (Sainju et al., 2002; Fageria et al., 2005; Dagel et al., 2014). Furthermore, cover crops improve water quality, increase mycorrhizal fungal activity, and affect soil temperature (Dabney et al., 2001).

Annual forages can serve as cover crops and have the potential to grow quickly under less than ideal conditions (Fageria et al., 2005). Legumes are widely used for their contribution of N to the soil through biological N_2 fixation (Sarrantonio, 2007). Additionally, species from the Poaceae and Brassicaceae family, are commonly used as winter annual cover crops (Cupina et al., 2011). In fact, several forage brassica species are used as cover crops in the Midwest. Brown or oriental mustard, black mustard (*Brassica nigra* L.), white or yellow mustard, turnip, forage rape, rapeseed, canola, and forage or oilseed radish are examples of the most common brassica cover crops (Gieske et al., 2016).

2.2.2. Challenges to grow cover crops

Under some circumstances, cover crops can reduce the cash crop yield by using up water stored in the soil profile, immobilizing N, and or producing excessive residues, hampering crop stand establishment or harvest (Dabney et al., 2001). However, the most obvious direct costs associated with cover crops include those for cover crop seed, labor, fuel, fertilizer, and herbicide or tillage to terminate the cover crop (Snapp et al., 2005).

All plants in the Brassicaceae family are non-host to arbuscular mycorrhizal fungi (AMF) and many of the species release anti-fungal isothiocyanates (ITC) affecting AMF colonization of the next crop in the rotation. However, White and Weil (2010) determined that radish did not affect AMF colonization of corn (*Zea mays* L.) following radish.

Cover crops can slow down the warming of the soil surface (Snapp et al., 2005; Stavi et al., 2012). In this way organic mulches reduce daily maximum soil temperatures (Vos and

Sumarni, 1997). These cool temperatures slow down the emergence and development of the subsequent crops in the spring (Hoyt, 1999; Dabney et al., 2001).

2.2.3. Soil health

Soil health, or quality, can be broadly defined as "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran, 2002). Cover crops improve soil health by increasing organic matter, improving soil structure, and facilitating more diverse and biologically active microbial communities (Blackshaw et al., 2005; Thomsen and Hansen, 2014). These soil properties will be impacted by cover crops according with the type of cover crop, type of soil, tillage and cropping system, management history, and climate (Blanco-Canqui et al., 2011).

Soil organic matter (SOM) has been defined as "the organic fraction of the soil exclusive of undecayed plant and animal residues" (SSSA, 2008). Organic matter includes thousands of different compounds that work in different ways to build a healthy soil (Sarrantonio, 2007). Additionally, SOM can be divided in three primary parts; a) small recent plant residues and small living soil organisms, b) decomposing (active) organic matter (OM) or detritus, and c) stable OM or humus (USDA-NRCS, 2012; Fenton et al., 2008). Soil organic matter composition is influenced by a variety of factors, where the type of vegetation and factors controlling microbial decomposition (climate) are two of the most important (Vancampenhout et al., 2009).

Soil organic matter influences the availability of N, P, S, and trace metals, water movement, soil structure, cation exchange capacity, soil color and temperature, and adsorption of chemicals (Nelson and Sommers, 1996). The active SOM or detritus contributes to soil fertility because the breakdown of these fractions results in the release of different nutrients. The humus or stable OM contributes to soil structure, soil tilth, and cation exchange capacity (Fenton et al., 2008). Soil organic carbon (SOC) is the major element, comprising 48 to 58% of the SOM (Nelson and Sommers, 1996). However, several studies have determined that the proportion of SOC in SOM is highly variable for a range of soils, even between horizons in the same soil (Nelson and Sommers, 1996). This SOC is found in several different compounds such as, lipids, aromatic compounds, polysaccharides, lignin, phenols, and N-compounds (Schumacher, 2002; Vancampenhout et al., 2009).

Cover crops can increase SOM into agricultural systems (Reeves, 1997), and also increase SOC concentration (Dabney, 1998; Weil and Kremen, 2007). Therefore, cover crops are efficient in C sequestration (Stavi et al., 2012). Cereal cover crops produce the largest amount of biomass and should be considered when the goal is to rapidly build soil organic matter (Cupina et al., 2011). Also, deep-rooted winter cover crops can add soil-building C, which is critical to soil quality and function, and can reduce nitrate losses by leaching in agroecosystems by scavenging N (Thorup-Kristensen et al., 2003; Fageria et al., 2005). Cover crops with a large and deep-rooted biomass may stimulate long-term soil C sequestration because root derived C has a lower turnover rate than shoot-derived carbon (Mutegi et al., 2013).

Generally, brassica cover crops do not increase SOM. Although they are high biomass producers, the low C:N accelerates its decomposition resulting in unchanged total SOM. In favorable conditions, radish biomass yield can exceed 7.8 Mg DM ha^{-1} (above and below ground) two months after sowing in the fall (Gruver et al., 2016). Planting radish into the small grains stubble can mitigate soil C depletion (Mutegi et al., 2011).

Studies assessing the relationships between soil physical properties and SOC in different crop rotations have reported variable results. An increase in SOC with diverse crop rotations is not always correlated with soil physical properties (Benjamin et al., 2008). However, other authors have reported that cover crops reduce soil penetration resistance, increase cumulative infiltration (Folorunso et al., 1992), and improve physical and hydraulic properties, increasing the SOC concentration significantly in the 0 to 7.5 cm depth (Blanco-Canqui et al., 2011). Typically, these changes are the result of roots forming new channels, improving soil structure (Makela et al., 2011).

Radish, Austrian winter pea, and a mix of these species generated highest, intermediate, and lowest soil bulk density impacts, respectively (1.67, 1.52, and 1.50 Mg m^{-3}), which was not related with the amount of SOC incorporated to the soil (15.9, 17.6, and 19.4 g kg^{-1}, respectively). The impact of cover crops on bulk density and concentration of SOC was greater at the 0- to 5-cm than the 5- to 10-cm depth (Stavi et al., 2012).

Cover crops, especially legumes, also improve soil tilth by increasing beneficial fungi and other micro and macro organisms (Sarrantonio, 2007). A glycoprotein, glomalin, produced by fungi, is central to the formation and stability of soil aggregates (Wright et al., 1999). Aggregates have several functions in the soil. Physical protection of soil organic matter, microbial community structure, oxygen diffusion, regulation of water flow, nutrient adsorption and desorption, and reduction of run-off and erosion. All of these processes affect SOM dynamics and nutrient cycling (Six et al., 2004). Highest water stable aggregate (WSA) and mean weight diameter of aggregates (MWD) were observed in soils after Austrian pea, compared with pea-radish mixture, and radish alone (Stavi et al., 2012).

Mycorrhizal fungi and *Rhizobium* bacteria create soil macro-pores and cycle nutrients that build soil structure and tilth (NRCS, 2013). Soil biology is the driving force behind decomposition processes that break down complex organic molecules and convert them to plant available forms (Friedel et al., 2001). The roots of cover crops help to sustain healthy organisms to restore soil structure (NRCS, 2013). When these cover crops are incorporated into the soil, they add SOM, improve soil structure, and increase soil biological activity (Carrera et al., 2007). Buyer et al. (2010) reported that adding rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* L.) into crop rotations increased soil microbial biomass (SMB). In addition, Stavi et al. (2012) determined that the earthworm (*Lumbricus terrestris* L.) population density increased with cover crops. An increase in earthworm population is associated with increased water infiltration and soil aggregate stability (Willoughby and Kladivko, 2002; Blanco-Canqui et al., 2011).

Excess of machinery traffic in field operations, accompanied with unpredictable rainfall, may result in soil compaction, especially in regions with heavy rainfall events (Williams and Weil, 2004; Chen et al., 2014). In compacted soils, root growth is restricted limiting access to water and nutrients stored in the subsoil (Williams and Weil, 2004; Chen and Weil, 2011). One of the solutions is deep tillage, but it is expensive, high energy cost, and the beneficial effect is short-lived (Horn et al., 2000).

Crop rotations that include tap-rooted species of cover crops may help alleviate the deleterious effects of soil compaction on plant growth by modifying soil physical properties (Chen et al., 2014). Brassicas long and thick taproot can penetrate compacted layers, breaking soil compacted layers more efficiently than the thinner and superficial roots of fibrous-rooted monocots (Chen and Weil, 2010). Once forage brassicas are winter-killed their roots decompose rapidly leaving channels that facilitates the root growth of a subsequent crop, enhancing infiltration and reducing compaction (Williams and Weil, 2004; Weil and Kremer, 2007). This is also known as 'biodrilling' (Cresswell and Kirkegaard, 1995). Images taken with a mini-rhizotron revealed that soybean (*Glycine max* (L.) Merr.) roots penetrated compacted layers by following the channels made by a cover crop the previous fall, increasing soybean grain yield (Williams and Weil, 2004). Multiple continuous small root channels (~1-mm in diameter) provide better infiltration than the discontinuous porosity generated by mechanical tillage (Weil and Kremer, 2007). Radish also reduces surface drainage (Gruver et al., 2016), almost eliminating run-off in the fall. Only a rainfall intensity of more than 260 mm h^{-1} can generate run-off (Weil and Kremer, 2007). However, winter-killed radish can easily release P to be lost in spring run-off (Liu et al. 2013, Liu et al. 2014).

The ability to break the compacted soil layers depends on the species. Radish roots have greater ability than cereal rye and rapeseed (Chen and Weil, 2010). Forage radish and rapeseed had double the root density than rye at 15-to 50-cm in depth in a compacted soil (Chen and Weil, 2010). In another experiment, soil cores taken from 55-cm in depth had 10 times more corn roots in the subsoil where radish was grown compared with no cover crop (Weil and Kremen, 2007). Also, in the soil surface above a compacted layers, corn root density was greater when rye was grown. Additionally, a mixture of radish and rye can help conserve soil water that can be used during summer water stress (Weil and Kremen, 2007).

The increased porosity created by cover crops roots enhances soil aggregate formation and stabilization which results in increased soil water-holding capacity (Prichard, 1998; Dabney et al., 2001), allowing crop roots to easily reach water in the subsoil (Dabney et al., 2001; Williams and Weil, 2004; Chen et al., 2007). Also, water conservation in the soil is increased by the residue left by cover crops, due to reduced evaporation. Excess of residue can hold water in wet years delaying planting especially in tilled soils (Clark et al., 2007). The use of water by cover crops may not cause a water shortage for the next crop where rainfall is adequate, as in humid regions, but may reduce yields where rainfall is low, as in semiarid regions (Unger and

Vigil, 1998). Water use by the cover crop may significantly decrease the amount of water stored in the root zone (Prichard, 1998). Additionally, faster water use by corn roots and more rapid recharge of soil water after rainfall in the subsoil was observed when corn was grown after forage radish compared with rye or no cover crop (Weil and Kremer, 2007). The rye cover crop, however, provided more residue mulch than the radish conserving more water in the soil above the plow pan (Weil and Kremer, 2007; Chen and Weil, 2010).

2.2.4. Soil erosion

Soils are most threatened by erosion when they are not covered with living plants or their plant residues. Annual crops such as corn or soybean provide coverage only four months of the year. In addition, crops used for silage do not leave enough protection between harvest and the next crop (Kaspar and Singer, 2011).

The use of cover crops has been recommended mainly to prevent soil erosion caused by winter and spring rains and wind (Dabney et al., 2001; Weil and Kremer, 2007). The efficiency of the cover crops to prevent erosion is related to how much they reduce the forces of soil detachment and transport (Kaspar and Singer, 2011). Cover crops control erosion directly by reducing the interrill erosion, through increasing the amount and duration of soil coverage by live plants or their residues. In this way, cover crops intercept raindrops, dissipating their impact energy, reducing the interril erosion (Kaspar and Singer, 2011). Additionally, cover crops or surface residues increase hydraulic resistance, which can slow the water flow velocity (Brown and Norton, 1994).

Cover crops reduce the erosive force of runoff water, reducing the overland flow of water through infiltration (Dabney, 1998; Stavi et al., 2012). This occurs because cover crops prevent surface sealing, increase storage capacity, and improve soil structure (Dabney, 1998). Also, cover crops increase SOC near the soil surface, building larger and more stable aggregates that are less susceptible to detachment (Dabney, 1998).

Austrian winter pea was slightly better in controlling soil erosion than radish or a binary mix (Stavi et al., 2012). However, the mix between these two species should be opted if the purpose is increasing N in the soil. Additionally, Gruver et al. (2016) mention that radish grows rapidly when planted in late summer or early fall, providing full canopy closure in about three weeks. Its canopy intercepts rain drops minimizing surface impact and detachment of soil particles.

2.2.5. Increasing soil fertility

In modern agricultural systems, it is necessary to develop nutrient management practices that optimize profit, preserve soil fertility, and protect natural resources (Dobermann and Cassman, 2002). The inclusion of cover crops can enhance soil fertility by scavenging leachable nutrients and/or adding N into the soil profile by legumes (Dabney et al., 2001; Sarrantonio, 2007).

2.2.5.1. Nitrogen fixation

One of the most important economic aspect provided by legume cover crops is their ability, under adequate conditions, to replace part of the requirement of N of non-legumes crops, by N_2 fixed biologically (Ebelhar et al., 1984; Weil and Kremer, 2007). Legume cover crop's N is a cheaper source of N than that from inorganic fertilizers, especially when price of N fertilizers are high. Legumes can reduce N fertilizer applications and production costs (Samarappuli et al., 2014).

Legume cover crops can fix different amount of N, depending on the species, crop management, and environment during the growth season. Typically, legumes grow slowly after emergence and usually produce less biomass yield than non-legume cover crops, but they can accumulate between 67 to 225 kg N ha^{-1} (Newman et al., 2007). Forage pea accumulated 3.3 Mg DM ha^{-1} in the fall, providing 116 kg N ha^{-1} for the next spring/summer crop in North Dakota (Samarappuli et al., 2014). Similarly, field pea grown alone or in mix with wheat, fixed 141 and 54 kg N ha^{-1}, respectively (Cupina et al., 2011).

Legume cover crops incorporated as green manure provided more than 110 kg N ha^{-1}, resulting in crop yields similar to those obtained by applying recommended rates of inorganic fertilizer (Tonitto et al., 2006). Sarrantonio and Scott (1988) determined that 157 kg N ha^{-1} were released to soil in about 10 days, when hairy vetch was incorporated into the soil.

2.2.5.2. Nitrogen scavenging

Nitrogen losses from crop fields caused groundwater contamination and eutrophication of surface water bodies (Isse et al., 1999; Dean and Weil, 2009) while gaseous N_2O losses contributed to GHG emissions and acid rain (Robertson and Vitousek, 2009). Available N in the soil can be lost to the environment through multiple pathways, including leaching, denitrification, and ammonia volatilization (Robertson and Vitousek, 2009). Leaching occurs when the NO_3-N in the soil solution is moved in the soil profile by mass flow beyond the root zone (Dean and Weil, 2009). Cover crops can be used to reduce NO_3-N losses by catching the residual N, improving nutrient efficiency, and increase N availability to the next crop (Thorup-Kristensen et al., 2003; Brennan and Boyd, 2012a-b; Gieske et al., 2016). Nutrient efficiency is enhanced when the nutrients in the cover crops are cycled back and are absorbed by subsequent cash crops (Robertson and Vitousek, 2009).

Scavenging NO_3-N from the soil will depend on how fast the cover crop root system grows (Meisinger et al., 1991; Sainju and Singh, 1997). Grass or brassicas reduce N leaching in about 70% on average and annual legumes about 20% (Liu et al., 2015). Brassicas are more effective than rye in reducing NO_3-N losses by leaching (Dean and Weil, 2009). Residual NO_3-N remaining in the top 1.0-m of the soil profile was 11.9 and 32.2 kg ha^{-1} for forage radish and rye, respectively. Also, NO_3-N remaining at the 1.0- to 2.5-m depth was 6.2 and 27.2 kg ha^{-1} for forage radish and rye, respectively, clearly indicating the effectiveness of forage radish to capture NO_3-N from deep soil layers (Kristensen and Thorup-Kristensen, 2004). Forage radish and rapeseed can scavenge more NO_3-N than rye because their root systems can explore a larger volume of soil (Chen et al., 2007; Weil and Kremen, 2007). Also, brassicas continue to grow until late in the fall, taking up the NO_3-N before it can be leached (Weil and Kremen, 2007). However, in cool weather conditions and when the planting is delayed in the fall, the NO_3-N uptake decreases (Vos and van der Putten, 1997). On the contrary, if the brassica cover crops are planted too early (July), NO_3-N uptake in the fall may be lower since the crop will start reproductive growth stage (Eichler et al., 2004).

In sandy soils, winter turnip established early in July or August has been shown to decrease NO_3-N leaching by over 90% (Macdonald et al., 2005), whereas a crop established later in August reduced NO_3-N leaching only in 19.7%, depending on environmental conditions, preceding crop, and planting time (Vos and van der Putten, 2004). Radish and cereal rye have demonstrated the capacity to take up 60 and 80% of the equivalent rate of fall-applied N, respectively (Lacey and Armstrong, 2015).

The accumulation of N in the cover crop tissue, and the ability to release it to the next crop depends on several factors, such as cover crop species, rainfall, temperature, length of growing season, and soil texture and fertility (Stute and Posner 1993; Decker et al., 1994). An effective nutrient scavenger releases the nutrient at the time the next crop requires it (Gieske et al., 2016). Cover crops deplete N from the soil solution, then when the cover crops die and the tissue is decomposed, the N is cycled back to the soil (Gieske et al., 2016). If mineralization of N from the cover crop residues is slow, N may not be available for the subsequent crop. On the contrary, if mineralization occurs too quickly, N can be lost before the subsequent crop start to accumulate N (Agehara and Warncke, 2005; Li et al., 2006; Gieske et al., 2016).

Soil temperature and water content determine N cycling. Microorganisms decompose organic matter faster at 80% of field capacity and 25°C than at lower temperatures (Guntiñas et al., 2012). Dissolved mineral, organic, and total N was significantly higher at 30°C than at 10°C and 20°C, after 7 weeks of soil sample incubation (Deressa, 2015). Conversely, incubation temperatures of 0°C, 15°C, and 30°C, did not change N mineralization rate the first four days of incubation (Koch et al., 2007). Nitrogen mineralization, denitrification, and ammonia volatilization can occur even at temperatures close to 0°C (Magid et al., 2004; Engel et al., 2011).

The C:N ratio of the cover crops also affects N mineralization from the residue (Thorup-Kristensen, 1994; Trinsoutrot et al., 2000). Pea residues in vegetative stage have a C:N less than 20, which speeds up decomposition rates (Copas, 2010). Legume residues with a C:N less than 20 can release N from mineralization within 10 to 20 days, whereas in more mature residue (C:N = 25-50), the release of N can take several months (Bruun et al., 2006). Soil microbial activity can peak the first week after incorporation of green pea residue (Lupwayi et al., 2004). Due to lower C:N ratios, brassicas can decompose and release the N from tissues into the soil more rapidly than grasses (Dean and Weil, 2009).

Radish, rapeseed, and white mustard have been reported to increase N accumulation and biomass production of the subsequent crop (Thorup-Kristensen, 1994; Vyn et al., 1999; Weinert et al., 2002). Both corn (V6 stage) and pre-nodulated soybean seedlings produced more dry matter and had higher tissue N when following forage radish compared with rye or no-cover crop (Weil and Kremen, 2007). However, in other studies, the cover crop provided no benefit to the subsequent crop, even though radish N accumulation was high (Isse et al., 1999). The N demand of the next crop must be synchronized with the N mineralization of the cover crop, in order to reduce N fertilizer rate without compromising the cash crop yield (O'Reilly et al., 2012). Some authors suggest that brassicas can have a better performance compared with rye, but only in early fall planting dates (Vos and Van Der Putten, 1997; Thorup- Kristensen, 2001). Also, several studies have determined that radish accumulates more N than rye, hybrid turnip and brown mustard (Strock et al., 2004; Dean and Weil, 2009; O'Reilly et al., 2012; Lacey and Armstrong, 2015).

2.2.5.3. Scavenging of P and other nutrients

In developed countries, P run-off from agricultural land to water sources is one of the primary causes of eutrophication (White and Weil, 2011). For that reason, mitigation of P and N losses from agricultural land to waters is a major challenge for modern agriculture (Liu et al., 2014, 2015). Cover crops can help to mitigate P losses by enhancing in nutrient cycling in the agroecosystem (White and Weil, 2011).

Members of the Brassicaceae family can solubilize recalcitrant forms of soil P by changing the pH of the rhizosphere (Marschner et al., 2007) and exuding organic acids (Shahbaz et al., 2006). Hence, when brassicas are grown as a cash crop or as a cover crop, soil P is accumulated in plant tissue, once plants die and decompose, P is available to the next crop (White and Weil, 2011). Winter turnip mobilizes fixed soil P through secretion of organic anions altering the soil pH in the rhizosphere (Makela et al., 2011). However, forage radish is unique in terms of P cycling because of its high tissue P concentration, rapid growth in the fall, and rapid decomposition in winter and spring (White and Weil, 2011). For that reason, forage radish can be used to remediate excessively high P soil, to increase concentration of P at the soil surface, and to improve fertility of low P soil (White and Weil, 2011). In a three-year experiment, forage radish increased P concentration in the upper 45 cm of soil, probably by translocation of P from deep in the soil (Weil and Kremen, 2007). In radish roots, P content is about 5 g kg^{-1}. Nearby the forage radish root holes, the P concentration is much higher than surrounding soil, which could be a result of biological, physical, and chemical interactions among plants, soil, and the environment (White and Weil, 2011). Forage radish P uptake in the fall ranged from 5.9 to 25 kg P ha^{-1} and in rye in the spring P uptake ranged from 3.0 to 26 kg P ha^{-1} (White and Weil, 2011). Forage radish slightly increased soil test P compared with three other brassicas cover crops and a sorghum [*Sorghum bicolor* (L.) Moench]-sudangrass [*S. bicolor* var. *sudanense*] at the 0- to 15-cm depth range (Wang et al., 2008). Also, the P soil test increased in the 0- to 45-cm depth range following three years of forage radish compared with treatments of rape, cereal rye, and no cover crop (Grove et al., 2007).

Even though the P scavenged by brassica cover crops is positive for nutrient cycling, increasing P concentration in the top of the soil profile may increase surface P losses by run-off. Liu et al. (2014) observed that nearly all the P in above ground biomass and roots of eight cover crop species was released after a few freezing/thawing cycles (FTC). Perennial ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.), and oilseed radish were the most susceptible to lose P quickly, compared with other cover crops (Liu et al., 2014). Even when cover crops are grown to reduce nutrient losses, exposed to FTCs, dead cover crop tissues can become a source of soluble P forms, increasing the potential of P loadings to water (Riddle and Bergström, 2013;

Liu et al., 2014). Heavy soil textures have a greater potential to lose P released from catch crop residues. A lower infiltration rate facilitates run-off of P. In sandy soils, macropores will carry P deeper in the soil profile decreasing run-off (Riddle and Bergström, 2013).

Cereal rye can increase exchangeable K concentrations in the first 5-cm of soil profile, probably by absorbing K from the soil and depositing the K-containing shoot and root residues on the soil surface (Eckert, 1991). Radish is an excellent K accumulator, with 40 g kg^{-1} of K in the root dry matter (White and Weil, 2011).

2.2.6. Pest management

Brassica cover crops produce toxic compounds that affect weeds, fungi, nematodes, and some insects when incorporated into the soil (Haramoto and Gallandt, 2005a). Brassicas must be mowed and incorporated to maximize their natural pest control activity, because toxic compounds are released only when the plant cells are broken (Clark et al., 2007). Glucosinolates, a S-containing compound, is hydrolyzed when comes into contact with the enzyme myrosinase. One of the resulting compounds is isothiocyanate (ITC) which has the potential to control weeds, disease, insects, and nematodes (Brown and Morra, 1997; Rosa et al., 1997; Sarwar et al., 1998; Kirkegaard and Sarwar, 1998; Gardiner, 1999; Haramoto and Gallandt, 2004; Weil and Kremer, 2007; Malik et al., 2008; Kirkegaard et al., 2008; Ackroyd and Ngouajio, 2011; Makela et al, 2011; Björkman et al., 2015). Additionally, other compounds from glucosinolate hydrolysis, organic cyanides and oxazolidinethione, may also be allelopathic (Brown and Morra, 1996).

2.2.6.1. Weed control

Cover crops can fill fallow periods between cash crops that might otherwise be vulnerable to erosion or weed establishment (Björkman et al., 2015). Brassica cover crops can rapidly cover the soil surface during the fall season, reducing weed growth (Chen et al., 2007). Several mechanisms of weed suppression have been reported. Weed seeds germination may be inhibited through shade-induced reduction in the ratio of red to far-red light, while subsequent growth and reproduction may be suppressed through competition for light, water, or nutrients (Holt, 1995). Additionally, brassica cover crop residues on the soil can inhibit the germination of small seeds during the spring (Chen et al., 2007). Brassica species can effectively suppress troublesome weeds, because glucosinolate breakdown products may inhibit weed seed germination by reacting with seed enzymes (Weil and Kremer, 2007). Rape, rye, and radish reduced strongly weed growth (Weil and Kremer, 2007).

Rapid and competitive fall growth, rather than allelopathy, is the primary mechanism of weed suppression by radish (Lawley et al., 2011; Lawley et al., 2012). Bioassays using radish-amended soil or aqueous extracts of radish tissues did not reveal any allelopathic activity to seed germination or seedling establishment (Lawley et al., 2012). Gruver et al. (2016) reported that radish can eliminate nearly all weed growth both during and for some time after radish has been winter-killed, but does not extend much into the summer. To obtain near-complete weed suppression, radishes should be planted early, six or more weeks before frost, at a relatively high population (more than 54 plants m^{-2}). Also, a vigorous biomass production is essential to obtain the maximum weed control provided by white mustard (Björkman et al., 2015). Ideally, a quick establishment of short-season cover crops will suppress weeds and prevent weed seeds germination (Björkman and Shail, 2013).

Some of the weeds suppressed by brassica cover crops are pigweed (*Amaranthus retroflexus* L.), shepherds purse (*Capsella bursa-pastoris* (L.) Medic), green foxtail (*Setaria viridis* (L.) Beauv.), kochia (*Kochia scoparia* (L.) Schrad.), hairy nightshade (*Solanum* *physalifolium* Rusby), puncturevine (*Tribulus terrestris* L.), longspine sandbur (*Cenchrus longispinus* (Hack.) Fern.), and barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.). However, pigweed was not inhibited by white mustard (Haramoto and Gallandt, 2005b). In other study, weed density of sixteen species decreased between 23 to 34% after brassicas were incorporated into the soil and the weeds emergence was two days later compared with fallow system (Haramoto and Gallandt, 2004). Radish grown as fall cover crop planted early in August reduced weed biomass in 65 to 95% (Gruver et al., 2016). The weed suppression provided by cover crops must be complemented with herbicide management to maintain a longer and complete control (Malik et al., 2008). Weed suppression with cover crops may be an important alternative weed management strategy, especially for organic farming. Brassica cover crops have the potential to be a valuable tool in vegetable cropping systems (Weil and Kremen, 2007).

2.2.6.2. Disease control

Brassica cover crops such as oilseed radish, brown mustard, and white mustard have been shown to decrease plant pathogen populations in the soil. Fungi sensitivity to the ITCs varies. *Gaeumannomyces* is the most sensitive genus to ITCs, *Rhizoctonia* and *Fusarium* have intermediate sensitivity, and *Bipolaris* and *Pythium* are the least sensitive (Sarwar et al., 1998). Allyl isothiocyanate, in particular, reduced the growth of the brown rot fungus [*Monilinis laxa* (Aderh. & Ruhland) Honey)] (Mari et al., 2008). Winter rape as a cover crop before potato (*Solanum tuberosum* L.), reduced the incidence of *Rhizoctonia* and *Verticillium* (Collins et al., 2006). Canola and rapeseed green manure decreased consistently rhizoctonia canker (*Rhizoctonia solani* J.G. Kühn), and common scab (*Streptomyces scabies*) incidence in potato (Larkin et al., 2010).

2.2.6.3. Insects and nematodes control

Cover crops can reduce insect damage by changing soil chemical and physical properties, releasing exudates and other compounds (Bugg, 1991), by changing above and belowground environmental factors, such as moisture levels and air movement, or by affecting the overall health of the crop (Sarrantonio and Gallandt, 2003). Cover crops attract beneficial organisms that feed on or parasitize insect-pests. Killed rye mulch was effective in attracting parasitoids and armyworm (*Pseudaletia unipuncta*) in a subsequent no-tillage corn crop (Laub and Luna, 1992), and suppressing colorado potato beetle (*Leptinotarsa decemlineata* Say) in no-tillage tomato production (Hunt, 1998). In addition, one investigation showed that allyl and benzyl isothiocynate forms reduced the growth of first-instar Lepidoptera larvae and final-instar larvae (Wadleigh and Yu, 1988).

Some positive effects on nematodes control have been reported as well. Rapeseed, arugula (*Eruca vesicaria* subsp. s*ativa* (Miller) Thell.), and mustard (*Sinapis spp. or Brassica spp.*) reduced nematode population in 80% in potato (Chen et al., 2007). In Wyoming, oilseed radish and white mustard reduced sugarbeet cyst nematode (*Heterodera schachtii* Schm.) population by 19 to 75%, with a high correlation with the cover crop biomass (Chen et al., 2007). In eastern Texas, researchers evaluated the effect of incorporating a wide variety of brassicas, 58 days before planting sweet potato (*Ipomoea batatas* L.). The radish cultivar Graza reduced populations of root knot nematode (*Meloidogyne* spp.) more than all other cover crops and also resulted in fewer ring nematodes (*Criconemella* spp.) at harvest than in the plots with no cover. Also, ring nematode reproduction rate was lower in 'Graza' plots than all other treatments (Steddom et al., 2008).

2.2.7. Agronomic management

2.2.7.1. Selection of cover crop species

The main benefits of cover crops can be gained by careful selection of appropriate plant species (Guldan and Martin, 2003). Fast-growing, drought-tolerant cover crops that require minimal management are preferred. Cover crops with fast germination and good seedling vigor are usually chosen because of their ability to compete with weeds (Cupina et al., 2011). Also, temperature and rainfall are the primary climatic variables affecting cover crop selection and potential utility. Warmer and wetter climate increase the potential benefits of cover crops (Dabney et al., 2001). Additionally, the decision about where and when to establish the cover crops will be related with soil characteristics, the crops sequence or rotation, window between sowing and harvest of cash crop, climate (frost free period, rainfall), availability of machinery, and others (Sarrantonio, 2007).

2.2.7.2. Sowing date

In order to maximize benefits of the cover crops, they need to be planted early, right after the cash crop harvest or interseeded into the standing cash crop. Adequate planting date will generate good root establishment and top growth before the cover crops go dormant, reducing winter kill, and increasing biomass production compared with later sowing dates (Balkcom et al., 2007). These cover crops can be under-sown in the previous main crop in spring, or planted after the main crop is harvested in fall. Under-sown cover crops are often perennial species that need a long growing period to become well established, while the after-sown crops are annuals that grow relatively fast (Liu et al., 2014).

One of the most important factors that affect the sowing date is the location. Sowing date is more critical in forage radish than in rye and rapeseed, in the mid-Atlantic, allowing the crop to take up significant amounts of soil N before it is frost-killed. Radish is frost tolerant but several continuous nights with -5°C can kill it (Weil et al., 2009). It grows best when planted from late July to early September but significant amounts of N can be captured by it when planted as late as 1 October (Weil et al., 2009). In the southern Great Lakes Region, optimum sowing date for mustard is recommended from 13 to 23 August for optimal growth and no later than early September for adequate stands (Björkman et al., 2015). Delaying the sowing date reduces dry matter yield accumulation during the fall and early winter (Villalobos and Brummer, 2013).

2.2.7.3. Sowing rate and sowing depth

Brassica cover crops (radish, mustards, and rapeseed) sowing rate fluctuates between 5.6 and 14.6 kg ha^{-1}. If broadcasted, the sowing rate must be increased in about 25 to 50% (Balkcom et al., 2007). Sowing rates must be corrected to pure live seed (PLS) if seed germination is below 80% (NRCS, 2011). In addition, the sowing depth should be between 6 and 19 mm for brassicas (Balkcom et al., 2007). Radish sowing rate fluctuates between 6.7 and 11.2 kg ha^{-1} if drilled or between 9 and 12.5 kg ha^{-1} if broadcasted. A high population stand of radishes (more than 54 plants m^{-2}) is desirable for a good weed suppression (Gruver et al., 2016).

2.2.7.4. Sowing method

Cover crops may be established using a variety of methods, including broadcasting, intersowing, drilling, frost/dormant sowing, manure slurry sowing, and aerial sowing (NRCS, 2011). Drilling the seeds ensures a better seedling establishment, but also is possible to broadcast the cover crop seeds into soybean or corn canopies that are beginning to senesce (Chen and Weil, 2011). By broadcasting cover crops on standing cash crops, several additional weeks of growth and increased N accumulation can be gained compared with cover crops planted after the cash crop harvest (Thomsen and Hansen, 2014). Broadcasting seed is faster than drilling, and if is done early into the standing crop may result in better stands than sowing done after the cash crop harvest (Frye et al., 1988). Also, broadcasting brassica cover crops seeds into winter wheat in July, in Denmark, generally resulted in a high biomass production in the fall, equal or higher than postharvest sowing (Thomsen and Hansen, 2014). However, NRCS (2011) states that seedbed preparation is essential to provide good seed-soil contact, because most cover crops will not perform well if broadcasted on a compacted or crusted surface. Cover crops established with a grain drill are much more effective and economical than those established by broadcasting.

2.2.7.5. Termination of cover crops

Cover crops are planted to get the benefits to soil health, but rarely are left to set seed before the next cash crop is planted, although in some cases the cover crop is grazed in the late fall (Legleiter et al., 2012). Some cover crops may be harvested to feed livestock directly as green chop or made into silage (Kratochvil et al., 2006). Because cover crops are produced between two cash crops, they should be terminated before the establishment of the next cash crop. If not terminated properly, cover crops have the potential to compete with the crop, reducing yield, and can slow down soil drying and warming in the spring (Legleiter et al., 2012). The timing of cover crop termination affects soil temperature, soil moisture, nutrient cycling, tillage and planting operations, and the effects of allelopathic compounds on the subsequent cash crop (Balkcom et al., 2007).

If cover crops are killed early in the spring, there is time to replenish soil water, warm the soil early, decrease phytotoxic effects of residues, give more time for residues decomposition, enhance cash crop planting operation, and increases N mineralization from lower C:N ratio cover crops (Balkcom et al., 2007). Decomposition over the fall, winter, and spring results in little residue remaining at the beginning of the next cropping season (Lawley et al., 2011). Conversely, killing the cover crop later, leaves residue available for soil and water conservation, better weed control, and more N_2 fixation from legumes (Balkcom et al., 2007). The five more common methods of terminating cover crops are: winterkill, tilling, mowing, roller-crimper, and applying herbicides (Legleiter et al., 2012).

2.2.7.6. Cover crop biomass production

Cover crops biomass production is the result of species, location, season/climate, and management (Balkcom et al., 2007). Mustard biomass fluctuates between 3.4 and 10 Mg DM ha^{-1}, radish between 4.5 and 7.8 Mg DM ha^{-1}, and rapeseed between 2.2 to 5.6 Mg DM ha^{-1} (Balkcom et al., 2007). Brassica cover crops planted by mid-September, can produce 3.0 to 5.0 Mg DM ha^{-1} of total biomass and take up 50 to 100 kg N ha^{-1} (Isse et al., 1999; Dean and Weil, 2009; Wang et al., 2010). Brassica cover crop biomass yields fluctuated between 4.8 and 6.2 Mg DM ha^{-1} and radish between 1.2 to 3.5 Mg DM ha^{-1} by the end of the fall in Minnesota (Geiske et al., 2016). Furthermore, radish produced 9.0 Mg DM ha^{-1} of aboveground biomass, and 4.1 Mg DM ha^{-1} below ground biomass (Ngouajio and Mutch, 2004). Biomass yield and soil coverage by cover crops in North Dakota, using brassicas, legumes, and cereals were superior with forage turnip cv. Pasja, and forage radish cv. Daikon. Among all cover crops Pasja obtained the greatest yield with 10.8 Mg DM ha^{-1} in 115 growth days, which was statistically different with the others 12 genotypes. Radish cv. Daikon was the second highest yield with 8.6 Mg DM ha^{-1} in the same growth period when compared with hybrid cv. Pasja (Samarappuli et al., 2014). Rapeseed can accumulate 6.7 Mg DM ha^{-1} aboveground biomass, with a N accumulation of 90 kg N ha^{-1} (Chen et al., 2007). Biomass of mustard planted in Michigan during spring ranged from < 0.5 to 4 Mg DM ha^{-1}, but planted in fall, the biomass ranged from 3.0 to 5.5 Mg ha^{-1} (Björkman et al., 2015).

2.3. Brassicas forage quality

Forage brassicas are more succulent and higher in nutritive value than almost any other type of forage (Smith and Collins, 2003), and provide forage when the majority of warm- and cool-season grasses and legumes are unproductive (Rao and Horn, 1986; Penrose et al., 1996; Altinok and Karakaya, 2003; Salmon and Dumbleton, 2006). Additionally, forage brassicas are fast growing, and offer great potential and flexibility for increasing stocking rate in late summer and fall, especially under drought conditions (Fustec et al., 2010). The nutritional content of brassica crops is variable and depends on environment but also of the degree of maturity of the plant at harvest time (Francisco et al., 2011). For some, but not all brassica species, nutritive value may be modified by cultivar selection, sowing rate, and time from sowing to harvest (Westwood and Mulcock, 2012).

Brassica forage crops are used as a primary source of energy for dairy and livestock production in northern Europe, where corn does not grow (Jung et al., 1984). Also, these species may serve as high energy forage crops at times when other forages availability may be limited (Griffin et al., 1984). Forage brassicas sown in spring are good alternative when there is summer drought, and also they can be grazed from August to December in the eastern United States (Jung et al., 1986). Besides of providing feed in quantity and quality, forage brassicas improved animal health and provided a break crop during a pasture renewal program (Salmon and Dumbleton, 2006).

2.3.1. Crude protein

Forage brassicas are highly productive, digestible forbs that contain relatively high levels of CP and digestible carbohydrates (Arnold and Lehmkuhler, 2014). Crude protein of the whole brassica plants have been reported to fluctuate between 130 to 280 g kg^{-1} (Smith and Collins, 2003; Teuber et al., 2009; Villalobos and Brummer, 2013). The hybrid Winfred had and CP content between 113 and 168 g kg^{-1}, lower than other brassicas (Ward and Jacobs, 2013).

Crude protein values are different depending on plant organ. Several authors have reported that CP content is about 25 to 60% greater in the above ground part than in the roots (Rao and Horn, 1986; Jung et al., 1986; Smith and Collins, 2003; Nichol et al., 2003; Villalobos and Brummer, 2013; Lemus and White, 2014). Kale and forage rape, accumulate about 43% more CP in the leaves than in the stems (Rugoho et al., 2014; Kaur et al., 2011).

Crude protein is influenced by species, cultivars, agronomic management and the environment. Crude protein content in shoots and roots depends on the cultivars used (Rao and Horn, 1986). Also, N fertilization and weather conditions influence CP content (Tiryakioglu and Turk, 2012). Increasing N fertilization and delaying sowing date in kale increased the leaf:stem ratio, and consequently the CP content. Low rates of N applied between sowing and harvest resulted in low CP in kale and rape whole plants (Westwood and Mulcock, 2012). Sowing rate also increased leaf:stem ratio (Albayrak et al., 2004). Higher CP was obtained at 20- and 30-cm o row spacing, than at 50-cm row spacing in turnip roots.

2.3.2. Fiber and digestibility

Forage brassicas have greater water content than most forages, about 900 g kg^{-1} of water (McCartney et al., 2009). This high water content can result in poor storage characteristics of the material when used for winter grazing or for stored feed. Additionally, brassica forages are relatively low in fiber and are readily digested, providing good energy to ruminants (Francisco et al., 2011). Neutral detergent fiber content fluctuated between 200 to 350 g kg^{-1} with a digestibility of 800 to 940 g kg^{-1} (Westwood and Mulcock, 2012; Villalobos and Brummer, 2013). For that reason, supplementary sources of fiber are highly recommended to ensure proper functioning of the rumen when only brassicas are grazed.

All the forage brassicas, in general, have high digestibility. The in vitro dry matter digestibility (IVDMD) of these species remains high most of its growth period allowing flexibility in their utilization (Jung et al., 1986; Rao and Horn, 1986). The IVDMD is usually between 750 to 950 g kg^{-1} (Smith and Collins, 2003). Kale usually has lower IVDMD due to their longer and fibrous stems (Jung et al., 1986; Kunelius et al., 1989).

Digestibility varies in different plant organs. The NDF in stems of forage rape Goliath was 323 g kg^{-1}, which was 60% and 26% higher than in leaves and petioles (130 and 239 g kg^{-1}, respectively) (Kaur et al, 2011). Teuber et al. (2009) reported values ranging from 730 to 910 g kg^{-1} and 930 to 970 g kg^{-1} of IVDMD in turnip and swede leaf and root, respectively. Digestibility is affected by the type of species, weather conditions, and management. Neutral detergent fiber was higher in plants from the earliest sowing date compared with the later dates, regardless of species and year (Wiedenhoef and Barton, 1994). Also, Pelletier et al. (1976), working with kale determined that the IVDMD was slightly affected by N fertilization rate and sowing date.

2.3.3. Energy and soluble carbohydrates

Another important component for animal production is the energy content of forages, which is expressed as metabolizable energy (ME). Forage brassica crops are usually a highly ME forage, with more than 2.9 Mcal kg^{-1} (Frischke, 2011). Forage brassicas can produce ME from 2.7 Mcal kg^{-1} to 3.5 Mcal kg^{-1} (Keogh et al., 2011; Ward and Jacobs, 2013; Garcia et al., 2008; Judson et al., 2013).

Energy content can be variable according with the species and the part of the plant. Apparently, swedes have greatest concentration of ME, averaging 3.3 Mcal kg^{-1} compared with kale with only 2.7 Mcal kg^{-1} (Westwood and Mulcock, 2012). Teuber et al. (2009) determined that the ME was higher in swede roots with 3.2 Mcal kg^{-1}, and lower in turnip, swede, and hybrid Winfred leaves with 2.2 Mcal kg^{-1}. Also, ME of kale declined from the upper to lower canopy (Rugoho et al., 2010).

The main reason for the high ME in brassicas is the high amount of water soluble carbohydrates (WSC) in the tissue, and lower structural carbohydrates (cellulose and hemicellulose). The content of WSC in a whole brassica plant is variable, ranging from 192 g kg^{-1} for first cut leafy turnip to 498 g kg^{-1} for swede (Westwood and Mulcock, 2012). In addition, Kaur et al. (2011) reported WSC content 680 g kg^{-1} and 220 g kg^{-1} in stem and leaf/petiole, in rape, respectively.

2.3.4. Minerals

Minerals in forages are essential nutrients for growth, but also supply animal requirements. Minerals content of Mg, Na, Fe, Mn, and Zn are reported to be greater in brassicas than those of cool-season grasses (Griffin et al., 1984). Conversely, Cu, Mn, and Zn content in brassicas are insufficient to supply the animal requirement (Smith and Collins, 2003). Also, Kunelius et al. (1989) and Lemus and White (2014) indicated that mineral composition of kale was adequate with the exception of Cu, Mn, and Zn, which would not satisfy the dietary requirements of ruminants. Iodine, Fe, and Cu supplements help to prevent anemia and goiter in cows (Lemus and White, 2014). Also, Ca, K, Mn, Fe, and B content in turnip leaf are adequate while other elements such as Fe, Cu, Mn, Zn, and B are in trace quantities (Francisco et al., 2011).

Levels of Ca, Mg, and P were influenced by species and planting date for rape, turnip and turnip hybrid (Wiedenhoef, and Barton, 1994). Forage brassicas grown in the summer have similar or superior content of Ca, Mg, K, Cu, Fe, Mn, and Zn than grown in the fall, although in the fall, N and P content was greater (Guillard and Allinson, 1989).

2.3.5. Animal performance

Forage brassicas can be adapted to different animal production systems (Smith and Collins, 2003), offering great potential and flexibility for increasing stocking rate in late summer and fall, especially under drought conditions (Fustec et al., 2010).

The most common use of forage brassicas in the United States has been grazing of fattening lambs and lactating ewes. Lambs can gain between 0.114 to 0.250 kg head $(hd)^{-1}$ day^{-1}, which is better than weight gain rates with other feed sources. Reid et al. (1994) conducted grazing trials with fattening lambs and breeding ewes for four years in late fall, and determined that daily weight gain of lambs varied strongly among the years. The average weight gain fluctuated from 0.019 to 0.330 kg hd^{-1} day^{-1}, but these weight gains were generally greater than with other forage resources such as tall fescue (*Festuca arundinaceae* L.), or orchardgrass (*Dactylis glomerata* L.) -red clover mixture. Lambs gained 0.129 kg hd^{-1} $day^{-1}$with brassicas which was slightly lower than the weight gain from ensiled grasses (Vipond et al., 1998). Also, fattening lambs had average growth rates of 0.230 kg hd^{-1} day^{-1} grazing on hybrid Winfred, over a 52 day period (Frischke, 2011). This hybrid cultivar must be grazed moderately, because lambs leave very low DM residue reducing the subsequent regrowth (Judson, 2010). Sheep gained between 0.110 and 0.241 kg hd^{-1} day^{-1} (Sprague et al. 2014), which is similar to a gain weight of 0.183 kg hd^{-1} day^{-1} reported by Dove et al. (2012). Forage brassicas are widely used to improve milk production in dairy cows. Clark et al. (1996) determined that supplementing pasture with 3.6 and 5 kg DM cow^{-1} day^{-1} of forage brassicas at two different research stations in New Zealand, milk solids increased between 26% and 18% respectively, compared with pasture only.

Crude protein and IVDMD of brassicas were above the requirements of dry pregnant breeding cows and also met the requirements of steers gaining 1.0 kg hd^{-1} day^{-1} both in fall and spring (Rao and Horn, 1986). In North Dakota, after 42 days of grazing (October 16 to November 27) pregnant cow's body weight increased 0.898 kg hd^{-1} day^{-1} across four different feed resources, but when fed turnips weight increased in 1.030 kg hd^{-1} day^{-1} (Neville et al., 2007). In the Chilean Patagonia, steers fed turnips *ad libitum* gained 1.215 kg hd^{-1} day^{-1} during 71 days of grazing (18 May to 28 July) (Hepp et al., 2008).

Additionally, the amount of methane released to the atmosphere was 22 to 30% less in lambs fed with fresh winter forage rape, compared with those fed perennial ryegrass. Apparently, the higher amount of readily fermentable carbohydrates, and smaller amount of structural carbohydrates in forage rape than in ryegrass, reduced methane release. This suggests that forage rape is a potential methane mitigation tool in pastoral-based sheep production systems (Sun et al., 2015).

2.3.6. Anti-nutritional compounds and animal health problems

Although infrequent, brassica crops can cause animal health disorders if grazing is not managed properly. The most common disorders can occur during the first two weeks of grazing while adjusting to the forage. The primary potential disorders are polioencephalomalcia (PEM), hemolytic anemia (mainly with kale), NO_3-N poisoning, and pulmonary emphysema. Other possible clinical disorders include bloat and rumen acidosis, and metabolic problems such as hypomagnesemia and hypothyroidism with goiter (Arnold and Lehmkuhler, 2014).

Nitrate is an antinutritional compound present in forage brassicas, caused mainly by excessive application of N fertilizers (Fletcher et al., 2010). Once these plants are consumed by ruminants, nitrate is transformed into nitrite in the rumen, transported to the blood stream and combined with hemoglobin, avoiding the transport of oxygen (Cash et al., 2006; Arnold and Lehmkuhler, 2014). Additionally, the excess of nitrate intake is excreted causing potential ground and surface water pollution (Kaur et al., 2010).

Concentrations of less than 0.35 mg NO_3-N g^{-1} DM are safe for all conditions and livestock classes; 0.35 to 1.13 mg NO_3-N g^{-1} DM are safe for non-pregnant animals, concentrations from 1.13 to 2.26 limit feed to 25 to 50% for some livestock, and greater than 2.26 mg NO_3-N g^{-1} DM are not recommended for feeding (Cash et al., 2006). Also, Fletcher et al. (2010) determine that concentrations greater than 2.0 mg NO_3-N g^{-1} DM reduce the performance of grazing animals. However, Nichol (2007) mention that 4.5 mg NO_3-N g^{-1} DM led to poor performance of grazing animals and, in extreme cases, death. Some reports suggest that the critical levels depend on individual animal factors, with important considerations being: animal condition (pregnant vs. non-pregnant), age, and animal type (Cash et al., 2006; Chakwizira et al, 2015a).

Forage rape is one of the brassica crops that can cause poisoning by NO_3-N, because the high accumulation of these compounds in its tissue (Kaur et al., 2010). This species has high NO_3-N content when is immature, for that reason forage rape needs to be grazed from about 7 weeks to about 13 to 15 weeks after sowing (Garcia et al., 2008). Brassicas grazed with less than 60 days of growth, have the potential to produce NO_3-N poisoning (Guillard et al., 1995). Kale also can accumulate high NO_3-N, for that reason the grazing in winter must be managed carefully (Fletcher et al., 2010).

The amino acid compound S-methyl-L-cysteine sulfoxide (SMCO) is an anti-nutritional compound accumulated in plants, and is unique to the Brassicaceae family (Arnold and Lehmkuhler, 2014). This compound can be accumulated in the plants by excessive applications of S fertilizers (Fletcher et al., 2010). Unlike with NO_3-N, SMCO increases with plant maturity and can be problematic during regrowth and after flowering. The SMCO is converted to dimethyl disulfide in the rumen, absorbed into the bloodstream, oxidizing hemoglobin (Arnold and Lehmkuhler, 2014). Kale, rape, and turnips can produce this toxicity, but most research indicates that kale is one of the most dangerous. This is extremely important in New Zealand, where kale is widely used as a supplement to pasture during winter. Consumption of SMCO may limit DM intake, the animal performance, causing hemolytic anemia (Rugoho et al., 2014). The content of SMCO increases in kale leaves from 1.4 to 6.2 g SMCO kg^{-1} DM between the first (16 September) and the last (6 December) harvest dates (Kunelius et al., 1989). However, this increment is lower than the content considered deleterious to animal health. Concentrations that exceed 15 g SMCO kg^{-1} DM can reduce the animal performance and threat animal's health (Fletcher et al, 2010).

Finally, glucosinolates present in brassicas are precursors of irritants that can cause colic and diarrhea. Large roots may lodge in the esophagus and lead to choking. Certain brassicas (specifically rape) can cause sunburn on light-skinned animals, especially when immature plants are grazed. Other potential problems include oxalate poisoning and off-flavoring of meat and milk (Arnold and Lehmkuhler, 2014).

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CHAPTER 3. AGRONOMIC STUDIES OF FULL-SEASON FORAGE BRASSICAS

3.1. Abstract

Forage brassicas have been included in livestock systems due to the high biomass yield production during a strategic time of the season, high quality feed for livestock requirements, their strategic use in crop rotations, and their relatively low cost of management and production. The objective of this study included: 1) to determine the most adapted and highest forage yielding full-season forage brassicas in North Dakota and 2) to determine the effect of sowing date, plant density, and N and S fertilization on forage yield and quality. Experiments were established at four locations Fargo, Prosper, Carrington, and Walcott, ND in 2012-2014. Experiment 1 included the evaluation of six forage brassica species and several cultivars of each species for a total of 20 species/cultivar. Experiment 2 included four species and three different sowing dates. Experiment 3 included three species and five plant densities. Experiment 4 included two crops, five N rates, and two S rates. In all experiments, leaf, root/stem, and total yield, and forage quality were recorded. Results indicated kale [*Brassica oleraceae* L. convar. *acephala* (DC)] and swede (*B. napus* L. var. *napobrassica*) were the highest forage yielding forage brassicas. Delaying sowing date reduced total forage yield in all species but did not influence forage quality. Plant density did not have an effect on forage yield or N accumulation averaged across environments and species. However, a significant interaction was observed in swede. The lowest plant density (33 plants m^{-2}) had higher root/stem yield while the highest plant density (200 plants m^{-2}) across all species had lower in vitro dry matter digestibility. Kale and swede leaf, root/stem, and dead matter yield increased up to 200 kg N ha^{-1} in a linear response indicating that these species could actually have a response to greater N rates. Sulfur and the interaction between N and S did not have an effect in forage yield and quality.

3.2. Introduction

The most common forages in grasslands and rangelands are grasses (*Poaceae* family) and legumes (*Fabaceae* family), but some other forbs or herbaceous broadleaf plants can also be used as forages (Barnes and Nelson, 2003). The *Brassicaceae* family has more than 3,000 species, but only some of them such as turnip [*Brassica rapa* L. var. *rapa* (L.) Thell], kale, swede, forage rape (*B. napus* L.) and brassica hybrids (*B. rapa* L. x *B. pekinensis* L.) have been grown for forage or pasture (Mitchell and Nelson, 2003; Smith and Collins, 2003). Forage brassicas have been cultivated for several centuries (Nadja, 1991; Smith and Collins, 2003). The past few decades forage brassicas have gained more importance in livestock-producing areas in New Zealand, Australia, North America (Jung et al., 1986; Jacobs et al., 2001; Nichol et al., 2003; Wilson et al., 2006, Neilsen et al., 2008; Keogh et al., 2011), Europe (Neilsen et al., 2008), and northern Asia (Bilgili et al., 2003).

Forage brassicas have been included in livestock systems due to the high biomass yield production during strategic times of the season, high quality feed for livestock requirements, strategic use in crop rotations, and relatively low cost of management and production (Rao and Horn, 1986; Ayres and Clements, 2002; Fulkerson, 2008; Neilsen et al, 2008; de Ruiter et al., 2009; Lemus, 2009; Rowe and Neilsen, 2010). They can resist lower temperature than most grasses and legumes (Jung et al., 1983; Jung et al., 1986; Smith and Collins, 2003, Keogh et al., 2011), and higher temperatures at the same time (Smith and Collins, 2003).

The maximum biomass yield production of forage brassicas is correlated with species/cultivar, management and environmental conditions (Ayres and Clements, 2002). In humid climates such as in New Zealand, kales are the most productive (Wilson et al., 2006; Brown et al. 2007; Fletcher et al., 2007, Fletcher et al., 2010a), followed by swedes (Gowers et al., 2006; de Ruiter et al., 2009). In North America, lower biomass yield for kale and swede has been reported (Jung et al., 1986; Kunelius et al., 1989). Forage rape is third after kales and swedes in biomass production (Jung et al., 1986; NDSU, 2003; Fletcher and Chakwizira, 2012; Judson et al., 2013), and turnips are normally less productive than latter (Kalmbacher et al, 1982; Jung et al., 1983; Jung et al., 1986; Rao and Horn, 1986; Penrose et al., 1996, NDSU, 2003). Hybrids are more variable in yield, producing more biomass when are hybrids from kale (Ward and Jacobs, 2013), than when are hybrids from turnip or forage rape (Griffin et al., 1984; Penrose et al., 1996).

Forage brassicas have higher nutritive value than almost any other forage (Smith and Collins, 2003). Crude protein content is very high, usually between 130 to 280 g kg^{-1} (Smith and Collins 2003; Teuber et al., 2009; Westwood and Mulcock, 2012; Villalobos and Brummer, 2013; Ward and Jacobs, 2013), with higher concentration in leaves than stems or roots (Rao and Horn, 1986; Smith and Collins 2003; Nichol et al., 2003; Kaur et al., 2011; Villalobos and Brummer, 2013). They are very low in fiber (Villalobos and Brummer, 2013), and are easily digested (Jung et al., 1986; Kunelius et al., 1989; Smith and Collins, 2003; Teuber et al., 2009; Francisco et al., 2011; Lemus and White, 2014). Leaves are more digestible than stems and roots (Rao and Horn, 1986; Rugoho et al., 2014). Metabolizable energy is high as well (Garcia et al., 2008; Frischke, 2011; Keogh et al., 2011, Westwood and Mulcock, 2012; Ward and Jacobs, 2013), with marked differences between leaves, stems, and roots (Teuber et al., 2009; Thompson and Stevens, 2012; Judson et al., 2013; Rugoho et al., 2014).

The sowing rate and crop density affect the crop performance and plant architecture (Stefanski et al., 2010). Soil temperature >10°C increases germination and emergence rate (Fulkerson, 2008). Shallow sowing depth (10 and 20 mm) improve emergence as well (Ayres and Clements, 2002; Smith and Collins, 2003; Salmon and Dumbleton, 2006; de Ruiter et al., 2009; Lemus and White, 2014).

The sowing date for forage brassicas grazed in summer should be in early spring (Aymes and Clemets, 2002). Species like kale or swede require longer growing season to achieve the maximum biomass yield (Jung et al., 1983; Wiedenhoef and Barton, 1994; Lemus, 2009; Benedict et al., 2013; Lemus and White, 2014). Delaying planting date from May to June or July greatly reduces forage yield (Dibb and Brown, 1964; Fulkerson and Tosell, 1972; Kunelius et al., 1987). Rape, radish, turnips, and hybrids need less days to complete their growing cycle (Jung et al., 1983; Wiedenhoef and Barton, 1994; Smith and Collins, 2003; Albayrak et al., 2004; Lemus, 2009; Frischke, 2011; Jacobs and Ward, 2011; Judson et al., 2013; Lemus and White, 2014), and are less or not affected by some delay in the planting (Kunelius et al., 1987).

High plant density reduces root sizes in turnip and swede (Smith and Collins, 2003; Albayrak et al., 2004), and stem diameter of forage rape (Cho et al., 1998). High density increases losses by trampling, and affects plant regrowth (Stefanski et al., 2010). Forage brassicas have different nutrient requirements, according with the soil fertility and the expected yield response (Wilson et al., 2006; de Ruiter et al., 2009). The most important nutrients are N, P, S, K, Mo, and B (Aymes and Clemets, 2002; de Ruiter et al., 2009). Nitrogen is the most important and required in larger quantities to high protein content in the tissues (Smith and Collins, 2003). The excess of N can concentrate anti-nutritional compounds (NO_3-N) in the plants, and produce water and air pollution (Chakwizira et al., 2015). Sulfur and N both are needed for protein synthesis (Grant and Bailey, 1993; Piri et al., 2012). A ratio of 7:1 N/S in the soil is optimum for brassica growth (Janzen and Bettany, 1984; Chen et al., 2007).

The specific objectives of this research were: 1) To identify brassicas species and cultivars with high biomass production and forage quality in North Dakota; 2) to determine the optimum sowing date of forage brassicas; 3) to determine the optimum sowing rate/plant density of different forage brassicas, and 4) to determine the forage brassicas response to different N and S fertilization rates.

3.3. Materials and methods

3.3.1. Experimental sites

Field experiments were conducted from 2012 to 2014 at three North Dakota State University (NDSU) research sites and one grassland preserve site. Sites were at Prosper (46°58´N, -97°3´W, elevation 284 m), Carrington (47°30´N, -99°8´W, elevation 475 m), Fargo (46°52´N, -96°47´W, elevation 274 m) and the Albert Ekre Grassland Preserve in Walcott (46°33´N, -97°07´W, elevation 296 m) ND, respectively. The soil type at Prosper is a Kindred-Bearden silty clay loam (Kindred: fine-silty, mixed, superactive, frigid Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll; Perella: fine-silty, mixed, superactive, frigid Typic Endoaquoll). The soil type at Carrington is Heimdahl loam (coarse-loamy, mixed, superactive, frigid Calcic, Hapludolls). The soil type at Fargo is; Fargo silty clay soil (fine, smectitic, frigid Typic Epiaquert). The soil type at Albert Ekre Grassland Preserve is Mantador-Delamere-Wyndmere fine sandy-loam (Mantador: coarse-loamy, mixed, superactive, frigid Aquic Pachic Hapludoll; Delamere: coarse-loamy, mixed, superactive, frigid Typic Endoaquoll; Wyndmere: coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll) (Web Soil Survey, 2013).

3.3.2. Experimental design and management

The experiments were: 1) species/cultivar experiments; 2) sowing date experiments; 3) sowing rate/density experiments, and 4) fertility experiments. The species/cultivar experiments were conducted at Fargo in 2012 and 2014, and Carrington in 2012 and 2013, evaluating six different species and several cultivars of each (Table 3.1). Some variations in the total species/cultivars occurred depending with the year of evaluation. The experiments were designed as a randomized complete block design (RCBD), with three replicates.

The sowing date studies were conducted at Fargo and Prosper in 2012 and 2014. The experimental design was a RCBD with three replicates, and a split-plot arrangement. The sowing date (three dates in 2012 and two dates in 2014) (Table 3.2) were the main plots. The sub-plots were the four forage brassica, turnip cv. Purple Top, kale cv. Maris Kestrel, swede cv. Major Plus, and winter canola cv. Riley.

The sowing rate/plant density studies were conducted at Fargo and Prosper in 2012 and 2014. The experimental design was a RCBD with three replicates, and a split-plot arrangement. Five plant densities were assigned to the main plot. The plant densities were targeted at 33, 44, 66, 133, and >200 plants m^{-2}. However, the final plant density determined at harvest time was different than the targeted density. The forage brassica kale cv. Maris Kestrel, swede cv. Major Plus, and forage rape cv. Dwarf Essex were assigned to the sub-plot.

The fertility studies were conducted at Prosper in 2012 and 2014, and Walcott in 2014. The experimental design was a RCBD with three replicates, and a split-plot arrangement. The forage crops kale cv. Maris Kestrel, swede cv. Major Plus were assigned to the main plot. The sub-plots were a factorial arrangement of five N rates (0, 50, 100, 150, and 200 kg N ha^{-1}) and two rates of S (0 and 40 kg S ha^{-1}).

Table 3.1. Species/cultivars, 1000 seeds weight and sowing rate of forage brassicas planted at Carrington, Fargo, Prosper, and Walcott, ND, in 2012, 2013, and 2014.

Species/Cultivar	Company	1000 seeds weight	Sowing rate†		
			2012	2013	2014
		g	kg ha^{-1}		
Kale					
Siberian	Agassiz Seeds	4.3	4.5	4.5	4.5
Maris Kestrel	Ampac	3.9	4.7	4.9	7.3
Dwarf Blue Bates	Agassiz Seeds	3.1	4.8	4.9	4.7
Sovereign	PGG	4.1		5.1	5.0
Swede					
Major Plus	Ampac	2.7	1.7	1.8	1.7
American Purple Top	Deer Creek Seed	3.1	1.7	1.8	1.8
Dominion	PGG	2.8	-	1.9	1.9
Turnip					
Purple Top	Millborn Seeds	2.4	-	2.4	2.3
Rack	Ampac	2.8	-	2.3	2.3
Pointer	Ampac	2.6	-	2.3	2.4
Hybrid‡					
Winfred	Millborn Seeds	4.7	5.6	5.8	6.2
Pacer	Ampac	3.0	5.7	5.6	5.6
Forage rape					
Rangi	Ampac	4.1	5.6	5.8	5.6
Barsica	Barenbrug	4.1	5.6	5.7	5.7
Dwarf Essex	Millborn Seeds	4.7	5.7	5.9	5.7
Bonar	Agassiz Seeds	4.7	5.7	5.6	5.7
Winter canola					
Riley	Kansas State Univ.	3.7	7.4	9.3	7.6
Griffin	Kansas State Univ.	3.9	6.2	6.1	6.2
Athena	Millborn Seeds	4.9	5.6	5.7	5.7
Summer	Millborn Seeds	3.3	7.5	8.8	8.2

† The sowing rates were corrected for % seed germination. Germination tests were conducted per every species/cultivars, every season.
‡ Hybrid Winfred (*Brassica rapa* L. x *B. oleracea* L.), hybrid Pacer (*B. rapa* L. x *B. napus* L.)

Traditional tillage was utilized to prepare the soil, based on one or two passes of a chisel plow in the fall to incorporate crop residues. In spring, one or two passes of a harrow and one pass of a roller were used to prepare the seedbed. All the forage brassica plots were seeded with a plot-cone planter (Wintersteiger, Plotseed XL, Salt Lake City, UT), using a sowing rate according to the recommendation for each species. Before planting, sowing rates were corrected by seed germination (Table 3.1). The germination tests were conducted each year, using the seeds bought or received from the seed or commercial companies. The same seed batches were used during the all years of experimentation. The percentage of germination determined in each species/cultivar, in each year, were used to correct the sowing rate in the corresponding year. The differences in the percentage of germination per each species/cultivar, each year, explain the different sowing rates used (Table 3.1). The sowing depth was approximately 8 to 15 mm.

The plots in the plant density study were seeded with the normal sowing rate for each species and then thinned to 20-, 15-, 10-, and 5-cm apart in the row. One plot in each replicate was left without thinning to obtain the higher density (> 200 plants m^{-2}). Each plot was 1.2 m wide and 6.1 m long (7.4 m^2), with 8 rows spaced 15-cm apart. Sowing and harvest dates of all experiments are indicated in Table 3.2.

During the first month after planting, grass weeds were controlled by applying Select Max™ (clethodim: (E)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]propy]5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) using 1.17 l ai ha^{-1}. Broadleaf weeds were controlled by hand-weeding one or two times during the season, depending on the weed pressure and regrowth. All the weed controls were conducted at rossete stage (between stage 2 and stage 3 (Harper and Berkenkamp (1975) and Theunissen and Sins (1984)) of brassica species and cultivars. The main insect problem in all studies was the crucifer flea beetle (*Phyllotreta cruciferae* Goeze), from emergence to adult plants. Asana XL (esfenvalerate: (S)-cyano(3-phenoxyphenyl)methyl (S)-4-chloro-alpha-(1-methylethyl)) was sprayed at the beginning of season 2012. Due to the inefficacy of this insecticide, thereafter flea beatle control was with Sniper (bifenthrin: (2 methyl[1,1'-biphenyl]-3-yl) methyl 3-(2-chloro-3,3,3-trifluoro- 1-propenyl)-2,2-dimethyl-cyclopropanecarboxylate) with 0.037 kg ai ha^{-1}. Flea beetle control required two applications per season in 2013 and 2014, and three applications in 2012. Helix Xtra (difenoconazole: 1-[2-[2-chloro-4-(4-chlorophenoxy)phenyl]-4-methyl-1,3-dioxolan-2-ylmethyl]-1H-1,2,4-triazole) was used as a seed treatment to prevent flea beetle damage during emergence using 1.5 L 100 kg $seed^{-1}$, however, apparent benefits in the control were not observed.

Table 3.2. Sowing and harvest dates and number of days from sowing to harvest for all forage brassica experiments at Fargo, Prosper, Carrington, and Walcott, ND, in 2012, 2013, and 2014.

	2012			2014		
Loc./Trial	Sowing	Harvest	No. days	Sowing	Harvest	No. days
<u>Fargo</u>						
S/CE[†]	25 Apr	16 Oct	174	28 May	16 Oct	141
SR/DE[‡]	25 Apr	11 Oct	169	29 May	24 Oct	148
FE[§]						
SDE[¶]						
Date 1	25 Apr	12 Oct	170	-	-	-
Date 2	9 May	12 Oct	156	27 May	24 Oct	150
Date 3	30 May	12 Oct	135	27 Jun.	24 Oct	119
<u>Prosper</u>						
SR/DE	2 May	25 Oct	176	23 May	22 Oct	152
FE	2 May	25 Oct	176	23 May	15 Oct	145
SDE						
Date 1	2 May	25 Oct	176	-	-	-
Date 2	15 May	25 Oct	163	4 Jun	10 Oct	128
Date 3	30 May	25 Oct	148	24 Jun	10 Oct	108
<u>Walcott</u>						
FE				16 May	22 Aug	98
<u>Carrington</u>					2013	
S/CE	26 Apr	20 Oct	146	16 May	26 Oct	163

S/CE[†]: Species/cultivars experiment; SR/DE[‡]: Sowing rate/density experiment; FE[§]: Fertility experiment, and SDE[¶]: Sowing date experiment.

The fertilization for all experiments was based on soil test results and aimed to a total availability (soil + fertilizer) of 100, 80, 100, and 20 kg ha^{-1} of N, P_2O_5,-K_2O, and-S, respectively. The fertility experiment had five N rates (0, 50, 100, 150, and 200 kg N ha^{-1}) and two S rates (0 and 40 kg S ha^{-1}). Fertilizers for each plot were weighed, placed in plastic bags and mixed the day before of the fertilization. The fertilization was surface applied two to three weeks after planting, in growth stage 2/3 for brassicas or the rosette stage. The fertilizers used were: urea (CH_4N_2O), mono-ammonium phosphate-MAP ($NH_4H_2PO_4$), potassium chloride-potash (KCl: NaCl), and gypsum ($CaSO_4$ x 2(H_2O).

Harvest for almost all experiments was conducted once in October, before the killing frost for forage brassicas. The species and cultivar experiment in Fargo and Carrington in 2012 was the only one harvested two times in the same season (July and October).

3.3.3. Evaluations

Soil samples were taken from 0- to 15-cm and 15- to 60-cm depths soon after planting. Soil samples from 0- to 15-cm were tested for pH, organic matter, SO_4, P, and K using standard methodology by the NDSU Soil Testing Laboratory (Franzen, 2013). The NO_3-N analysis was performed from the soil samples taken at 0- to 15-cm and 15- to 60-cm depth, using the method of transnitration of salicylic acid (Cataldo et al., 1975).

Before harvest, average plant height was measured by taking three heights in each plot, from the soil surface to the longest vegetative part of the plant (held vertically). Harvest was conducted by hand using a 1 m^2 square, to determine both above and below ground biomass. A sample from the total forage biomass (leaf and/or root/stem) per each plot was taken to analyze forage quality. The whole plant biomass harvested was divided into leaves and stems (kale, forage rape, winter canola, Ethiopian cabbage, and hybrids) and into leaves and roots (turnip, swede, and some hybrids). Enlarged roots were removed from the soil pull them up or using a shovel, to harvest the maximum of enlarged root tissue. Additionally, senescent and dry material on soil surface and under the canopy was measured and characterized as dead matter. Total forage biomass yield (leaf + root/stems) plus dead matter represented total biomass yield. Once separated, leaves of each sample were placed in burlap bags and then tagged. Roots were washed and then chopped in a food processor (Sunbeam, Model Le Chef, Chicago, IL), leaving pieces of 5-mm thick or less. Stems were cut longitudinally with a knife in four or more parts according with the thickness of the stem. Stem and root pieces were placed in burlap bags or mesh plastic bags and then tagged. All the samples bags were weighed to determine the wet weight and dried at around 43.3°C. Samples remained in the driers several days until the weight loss was stabilized. Samples were weighed to obtain the dry weight. Dried samples were ground in a mill (Wiley Mill standard Model Nº3, Philadelphia, PA) to 1-mm mesh and then sent for forage quality analysis.

Chemical analysis for 50 leaf, stem, and root samples were conducted at Animal Sciences Nutrition Laboratory at North Dakota State University. The results were used to build calibration equations to determine nutritional values for near infrared reflectance spectroscopy (NIRS) analysis. The components determined were crude protein (CP) (Kjeldahl method) (Speirs and Mitchell, 2013), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), 48-h neutral detergent fiber digestibility (NDFD), ash, and in vitro dry matter digestibility (IVDMD). Total digestible nutrients (TDN) were then calculated from the above parameters according to Undersander (2004). Then, all samples were analyzed in a near infrared reflectance spectroscopy (Foss-Sweden Model 6500, Minneapolis, MN), for the same forage quality components indicated previously, in Dr. Undersander's laboratory, University of Wisconsin, Madison, following the methods described by Abrams et al. (1987).

The N accumulation (N total) in each species/treatment plot was determined from the CP content, obtained from NIRS results. Nitrogen content was calculated with the equation: N =

CP/6.25. Nitrogen accumulation was calculated arithmetically multiplying the above and below ground forage biomass yield in kg ha^{-1} by the N content. Total N accumulation (kg N ha^{-1}) of forage produced was calculated using the N concentration (g kg^{-1}) in the tissue (leaf or root/stem), times the total biomass yield produced per ha.

3.3.4. Statistical analysis

The statistical analysis was conducted using standard procedures for a RCBD or a RCBD with factorial or split-plot arrangement depending on the experiment. Each location/year combination was defined as an environment and was considered a random effect in the statistical analysis. The different treatments such as species/cultivars, sowing rates, densities, and fertilization rates were considered fixed effects. Analysis of variance and mean comparisons were conducted using the procedure Mixed of SAS (SAS, 2014). Error mean squares were compared for homogeneity among environments according to the folded *F*-test and if homogeneous, then a combined ANOVA was performed across environments. Treatment means separation was determined by *F*-protected LSD comparisons at the $P \leq 0.05$ probability level. Regression analysis was conducted in the fertility study to determine the response to N. Leaf root/stem, and dead matter yield values were converted to a relative scale from 1-100%, to account for the yield variation in different locations and years. Linear and quadratic regression models were constructed with both, relative and absolute values, and tested with the corresponding error. The regression models were all at $P \leq 0.05$ level of significance.

3.4. Results and discussion

3.4.1. Rainfall, temperature and soil test

The historical 25-year rainfall yearly average is 384, 467, 445, and 578 mm for Carrington, Fargo, Prosper, and Walcott, respectively (Fig. 3.1) (NDAWN, 2016). The rainfall was below the 25-years historical average, in almost all months during the growing season (April-October), in 2012 and 2014 in Carrington, Fargo, Prosper, and Walcott. In 2013, rainfall was above the 25-years rainfall average in Fargo and Prosper, but not in Carrington. The most critical rainfall deficiency was in Fargo and Prosper in 2012, with only 244 and 242 mm of rainfall during the growing season, compared with 467 and 445 mm of 25-years rainfall average. In general, the rainfall between sowing and emergence time was adequate, with the lowest amount of rainfall (43.4 and 46.2 mm) in May, in Fargo and Prosper in 2012. Several authors indicate that adequate soil water content and warm soil temperature (>25ºC) result in early emergence and establishment (Jung et al., 1983, Rao and Horn, 1996; Keogh et al., 2011). The most limiting water supply in the experiments was during vegetative growing stage. In Carrington, in September 2012 and August 2013, and Fargo in September 2012, rainfall was 5.6, 12.1, and 1.3 mm, respectively; the driest months observed during these experiments. The most severe driest months could have limited growth of crops in some of the experiments at different locations. Previous research has reported a major impact on growth and dry matter accumulation of forage brassicas when exposed to water deficit (Fletcher et al., 2010b).

The minimum and maximum temperature recorded during 2012, 2013, and 2014 were relatively similar to the 25-year average (Fig. 3.1). The highest minimum and maximum temperatures were observed in July and August, and the lowest minimum and maximum between December and February. The hottest summers were observed in 2012 in Carrington, Fargo, and Prosper, with about 3°C above average. The 2013 and 2014 summers were similar to the 25-yr average temperature in all experimental sites except in Walcott. These temperatures are adequate for plant growth of *Brassica* spp. (de Ruiter et al., 2009).

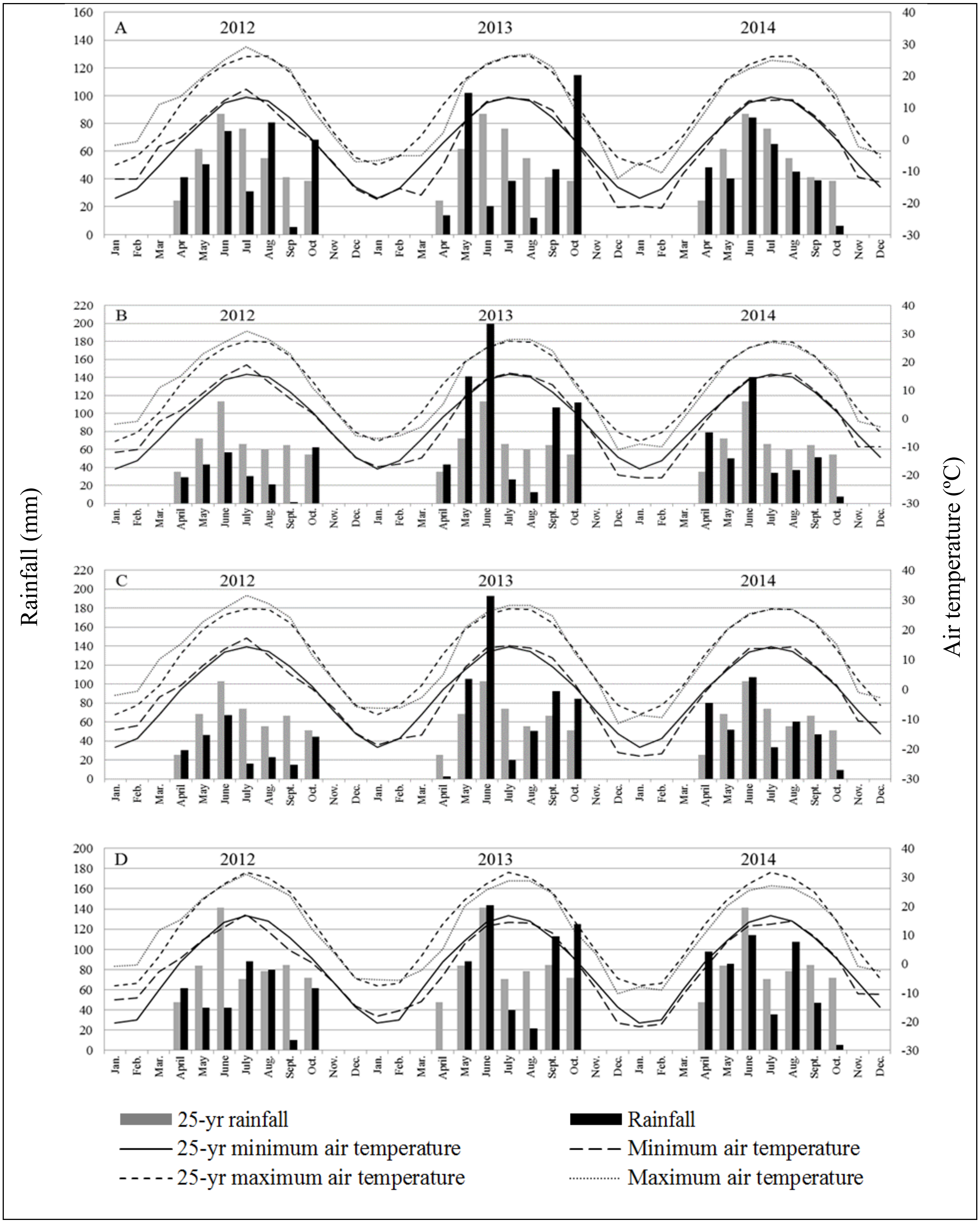

Fig. 3.1. Monthly average minimum and maximum air temperatures and monthly total rainfall in 2012, 2013, and 2014 compared with the 25-yr (1990-2014) average in Carrington (A), Fargo (B), Prosper (C), and Walcott (D).

The average temperature of bare soil was between 12.7 and 21°C one week after sowing in the four research sites (data not presented). This temperature range is considered optimal for fast germination and emergence (Smith and Collins, 2003), allowing plants to emerge in 10 days or less after sowing, similarly to what was reported by Jung et al. (1986).

Soil tests results are presented in Table 3.3. The fertilization for all experiments was based on soil test results and aimed to a total availability (soil + fertilizer) of at least 100, 80, 100, and 20 kg ha^{-1} of N, P_2O_5, K_2O, and S, respectively, avoiding any nutrient limitation to the crops. Nitrogen, P, K, S, are the most important macronutrients in forage brassicas (Ayres and Clements, 2002; de Ruiter et al., 2009). The soil NO_3-N was variable between years and among experimental sites and was between 31 and 202 kg ha^{-1} at the standard samplings depth of 0-60 cm (Franzen, 2013). Available N in the soil was supplemented by fertilizer application because brassica's productivity and forage quality are highly dependent on available N (Smith and Collins, 2003; Jacobs and Ward, 2011). Available SO_4-S were medium to low, with values between 8 and 13 kg ha^{-1}. Phosphorus was low only in Carrington (8 mg kg^{-1}). At all other locations available P was higher than the 16 mg kg^{-1} threshold for most crops (Franzen, 2013). In general, soil K was in adequate level and soils testing below 250 mg kg^{-1} were supplied with fertilizer. The pH was between 6.9 and 7.9 and organic matter was almost twice as high in Fargo, than at Carrington, Prosper, and Walcott.

3.4.2. Forage brassica species and cultivars performance

The analysis of variance combined across two environments, Carrington and Fargo, in 2012, for leaf yield and total N is presented in Table 3.4. The species (species and cultivars, henceforth 'species') main effect was not significant for the leaf biomass yield and total N in the first harvest. In the second harvest, leaf biomass yield and total N were different among species.

Table 3.3. Soil test at the experimental sites in Fargo, Prosper, Carrington, and Walcott, ND, for different forage brassica experiments, in 2012, 2013, and 2014.

Location/ trial	N- NO_3 (0-15 cm)	N-NO_3 (15-60 cm)	N-NO_3 (0-60 cm)	S-SO_4‡	P	K	OM	pH
	------------------------kg ha^{-1}--------------------				-----mg kg^{-1}-----		g kg^{-1}	
				2012				
Carrington								
S/CE	73	98	171	-	8	120	30	7.3
Fargo								
S/CE†	63	98	161	-	17	430	59	7.9
PDE	24	27	51	-	15	380	66	7.7
SDE	25	44	69	-	18	375	79	7.6
Prosper								
PDE	25	37	62	-	25	320	47	7.2
SDE	55	44	99	-	33	405	47	6.9
FE	17	27	44	-	29	305	39	7.2
				2013				
Carrington								
S/CE	44	47	91	4	7	125	27	7.1
				2014				
Fargo								
S/CE	34	121	155	13	15	315	67	7.3
PDE	25	104	129	12	10	390	60	7.8
SDE	19	83	102	10	4	295	67	7.5
Prosper								
PDE	53	111	164	9	22	360	35	7.5
SDE	49	104	153	7	27	340	35	7.5
FE	57	145	202	10	24	285	38	7.3
Walcott								
FE	6	25	31	8	51	397	29	7.4

† S/C= Species/cultivars experiment; PD= Plant density experiment; SD= Sowing date experiment; F = Fertility experiment.

‡ S-SO_4, pH, organic matter (OM), P-Olsen, K from 0-15 cm depth.

When both harvests were combined, leaf biomass yield and total N were different among species. Root/stem biomass yield, root/stem total N, and the biomass of dead matter accumulated below the canopy were different among species (Table 3.5). leaf and root/stem biomass yield, the total N of forage yield, and the total biomass yield (leaf, root/stem, and dead matter) were not significantly different among species. Environment by species interaction was significant for the total leaf yield and the total leaf and root biomass s summed up, but since environments were considered random, discussion of results will be based on the significance of main effects only.

In the second harvest, leaf biomass yield fluctuated between 1.8 Mg ha^{-1} in winter canola cv. Griffin and 6.4 Mg ha^{-1} in kale cv. Maris Kestrel (Table 3.6). The leaf yield in 'Maris Kestrel' was 58% of the total forage yield (leaf + stem) and 67% of the total biomass yield (leaf+ stem + dead matter), which were higher than the proportion of leaves reported by Stephen (1976) and Fletcher et al. (2007). The leaf proportion reaches 75%, 90 days after sowing, decreasing to 25% at 270 days after sowing (Stephen, 1976). All kale cultivars had significantly higher yield than swede, hybrids, forage rape, and winter canola cultivars. The higher biomass yield of kale cultivars compared with the other four species was most likely due to the longer time available to accumulate biomass since it kept growing well into late fall (November) which has been observed before (Wiedenhoef and Barton, 1994; Jung et al., 1983, and Jung et al., 1986). Cultivars within a same species did not have different biomass yield with the exception of kale cv. Maris Kestrel which had significant higher yield than the cv. Siberian. This was probably because 'Siberian' is a leafy and stemless cultivar used mainly for human consumption not forage. Kales and swedes were harvested only once while all other species were harvested twice. This could explain the lower yield of the other forage brassicas evaluated compared with kale. Two harvests in the season likely reduces total yield, since new regrowth after the first harvest does not intercept solar radiation at its full potential until it reaches optimum leaf area index (LAI) (Brown et al., 2007). Likewise, total N was also significantly higher in kale cultivars. Kale total N fluctuated between 143 and 160 kg N ha^{-1} while the other species fluctuated between 61 and 110 kg N ha^{-1}. Similar results were reported by Teuber et al. (2009) indicating kale total N was greater than other brassica species and increased when harvested later in the season.

Total leaf yield averaged 5.7, 3.1, 8.4, 7.7, and 6.9 Mg ha^{-1} for kale, swede, hybrid, forage rape, and winter canola cultivars, respectively (Table 3.6). The hybrid cv. Pacer total biomass yield was 8.8 Mg ha^{-1} and was greater than all swede and kale cultivars, except 'Maris Kestrel'. Although yield values among different studies are not comparable, in general, total leaf biomass yield was within the yield range observed in New Zealand (Gowers et al., 2006). All cultivars of hybrids, forage rape, and winter canola were not significantly different among them.

The total N averaged 152, 100, 215, 262, and 194 kg N ha^{-1} for kale, swede, hybrid, forage rape, and winter canola cultivars, respectively. Only swede cultivars had significantly lower total N than all cultivars of hybrids, forage rape, and winter canola.

All species evaluated had higher leaf yield than root/stem except swede cultivars (Tables 3.6 and 3.7). Swede accumulated between 60 to 67% of the total forage biomass in their roots, which was consistent with the results reported by Gowers et al. (2006). Similarly, the leaf/root ratio of swede cv. Dominion was 1:1 and 1:3 in four and six months after sowing, respectively (Hepp et al., 2012). The root and stem biomass yield for all species/cultivars evaluated fluctuated between 0.4 and 5.8 Mg ha^{-1}. Conversely, cultivars that produce thick stems and not enlarged roots (kale, hybrid, forage rape, and winter canola) accumulated lower biomass yield with the exception of kale cv. Maris Kestrel. The root/stem total N fluctuated between 8 and 134 kg ha^{-1}. Swedes had significantly higher total N than all other species and cultivars. Similarly, Teuber et al. (2009) reported the highest total N in swede roots in comparison with turnip, kale, and hybrids.

Table 3.4. Analysis of variance and mean squares for forage brassica leaf biomass yield (first and second harvest), total biomass yield, and total N in two environments, Carrington and Fargo, ND, in 2012.

Source of variation	df[‡]	Leaf yield harvest 1	Total N harvest 1	df	Leaf yield harvest 2	Total N harvest 2	Total leaf yield	Total leaf N
Env[†]	1	120161**[§]	51.4*	1	244167*	249.0**	603988***	468.0**
Rep(Env)	4	3028*	3.9**	4	955	4.5*	4433*	12.6***
Sp	9	2031	0.8	14	11560***	6.2***	17889*	10.1**
Env x Sp	9	1683	1.2	14	832	0.6	4974**	2.3
Error	36	1094	0.8	56	1208	1.3	1723	1.8
CV, %		21	22.3		34	37.9	20	23.4

[†] Env=Environment, Rep=Replicate, Sp= forage brassica species and cultivars.
[‡] More than one column of df is due to different number of species/cultivars evaluated between harvest 1 and 2.
[§] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively. Mean squares values were divided by 1000 for better fit on the table.

Table 3.5. Analysis of variance and mean squares for forage brassica root/stem, leaf and root yield, total N, dead matter yield, and total biomass yield in the last harvest in two environments, Carrington and Fargo, ND, in 2012.

Source of variation	df	Root/stem yield	Total N root/stem	df	Leaf and root/stem yield	Total N leaf + root/stem	Dead matter yield	Total yield[¶]
Env[†]	1	157	1.2	1	575423***	512.0**	29668***	343771**
Rep(Env)	4	1166*[‡§]	1.0*	4	8696*	20.2***	417	6812
Sp	14	18786***	10.0***	14	10384	4.5	5026***	12562
Env x Sp	13	702	0.3	14	5374*	1.9	359	6334
Error	54	395	0.3	56	2407	2.4	1039	4303
CV, %		32	41.0		18	22.2	35	18

[†] Env=Environment, Rep=Replicate, Sp= forage brassica species and cultivars.
[‡] More than one column of df is due to different number of species/cultivars evaluated for root production
[§] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively. Mean squares values were divided by 1000 for better fit on the table.
[¶] Total yield includes leaf, roots/stem, and dead matter below the canopy.

Table 3.6. Mean biomass leaf yield and total N of forage brassica of two harvests averaged across two environments, Carrington and Fargo, ND, in 2012.

Species/cultivar	Harvest 1		Harvest 2		H1 + H2	
	Leaf yield	Total N	Leaf yield	Total N	Leaf yield	Total N
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
Kale						
Siberian	-	-	5.0	143	5.0	143
Maris Kestrel	-	-	6.4	153	6.4	153
D. Blue Vates†	-	-	5.8	160	5.8	160
Swede						
Major Plus	-	-	3.6	110	3.6	110
Am. Purple Top	-	-	2.6	90	2.6	90
Hybrids						
Winfred	4.6	128	3.3	97	7.9	225
Pacer	6.1	133	2.7	72	8.8	204
Forage Rape						
Rangi	5.0	138	2.6	74	7.6	212
Barsica	5.4	136	2.9	83	8.3	219
Dwarf Essex	4.9	125	1.9	62	6.8	187
Bonar	5.2	134	2.8	85	7.9	219
W. Canola						
Riley	4.7	120	2.6	89	7.3	209
Griffin	5.5	137	1.8	61	7.3	198
Athena	4.2	101	2.6	77	6.8	179
Summer	4.3	116	2.0	73	6.3	189
LSD (0.05) ‡	NS	NS	1.1	30	2.8	59

† D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.

‡ LSD= Least significant difference used as mean separation method, with a significance of 0.05.

Table 3.7. Mean root and root +leaf yield, total N, biomass yield of dead matter, and total biomass yield averaged across two environments, Carrington and Fargo, ND, in 2012.

Species/cultivar	Root/stem Biomass yield	Root/stem Total N	Leaf + root/stem Biomass yield	Leaf + root/stem Total N	Dead matter Biomass yield	Total[¶] Biomass yield
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}
Kale						
Siberian	0.7	21	5.7	163	4.2	9.9
Maris Kestrel	4.8	97	11.1	250	3.2	14.3
D. Blue Vates[†]	1.6	26	7.4	185	3.3	10.7
Swede						
Major Plus	5.8	134	9.3	244	4.8	14.2
Am. Purple Top	5.3	131	7.9	221	4.3	12.2
Hybrids						
Winfred	1.7	35	9.6	260	2.5	12.1
Pacer	0.4	8	8.9	213	2.3	11.2
Forage Rape						
Rangi	1.4	29	9.0	240	2.2	11.2
Barsica	1.5	30	9.8	249	1.8	11.6
Dwarf Essex	0.9	22	7.8	209	2.3	10.1
Bonar	1.2	25	9.1	245	2.6	11.6
W. Canola						
Riley	1.0	26	8.1	235	2.5	10.6
Griffin	0.7	16	7.9	214	2.3	10.2
Athena	0.7	18	7.5	196	1.9	9.4
Summer	1.0	25	7.3	214	2.8	10.1
LSD[‡] (0.05)	1.0	22	NS	NS	0.7	NS
LSD[1§] (0.05)	1.2	27				

[†] D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.

[‡] LSD= Least significant difference used as mean separation test, with a probability of 0.05.

[§] LSD[1] is to compare “Pacer” with other cultivars. The LSD is different because this cultivar was not in all experiments combined.

[¶] Total yield includes leaves, roots and dead matter below the canopy.

Leaf and root/stem yield, total N, and total biomass yield including leaf, root/stem, and dead matter were not different among cultivars and species. However, several other authors have found differences in forage yield between species and cultivars likely due to climatic and soil differences (Jung et al., 1986; Penrose et al., 1996; Gowers et al., 2006; Keogh et al., 2011). Dead matter fluctuated between 1.8 and 4.8 Mg ha^{-1}. The largest leaf loss occurred in both swede cultivars and in kale cv. Siberian, both species were harvested only once accumulating biomass during the whole growing season. The low light quality under the canopy likely induced leaves to senesce with negative net photosynthesis, a response common to most plant species. On the contrary, forage rape, hybrid, and winter canola were harvested at 75 to 84 days after sowing, thus leaf loss was much less, since light quality under the canopy did not decrease until near to the second harvest.

The analysis of variance for leaf quality components of species harvested twice (hybrids, forage rape, and winter canola), across two environments, Carrington and Fargo in 2012, are presented in Table 3.8. The species main effect was significant for ash, CP, ADL, and TDN, but harvest time main effect was not significant for any components. The interaction species by harvest was only significant for CP and ADL.

The mean ash content fluctuated between 138 and 208 g kg^{-1}, with the highest content in hybrid cv. Pacer (Table 3.9). The CP content was almost always lower in the first harvest compared with the second harvest, except for hybrid cv. Winfred. This result differs from Rao and Horn (1986) and Teuber et al. (2009) who determined that almost all species/cultivars evaluated declined in CP content in later harvest dates. The decline of CP content could be attributed to increased dry matter accumulation rate causing a dilution effect (Rao and Horn, 1986). The highest differences were between hybrid cv. Pacer in the first harvest and winter canola cv. Summer in the second harvest, with 133 and 223 g kg^{-1} of CP, respectively. The CP values observed in the present study are slightly lower than concentrations reported by Teuber et al. (2009) in similar forage brassicas. The ADL content was almost always higher in the first harvest compared with the second, in addition the higher content was determined in the hybrid cv. Pacer, in both harvest time (Table 3.10). The highest difference was determined between hybrid cv. Pacer and winter canola cv. Summer, with 44 and 25 g kg^{-1}, respectively. The TDN fluctuated between 701 and 780 g kg^{-1}, for hybrid cv. Pacer and forage rape cv. Barsica, respectively, the only two cultivars that were significantly different (Table 3.11). This high TDN is typical of forage brassicas which have very high digestibility compared with other common forages such as alfalfa or corn silage.

The analysis of variance for leaf quality components of species harvested just once (kales and swedes), across two environments, Carrington and Fargo in 2012, are presented in Table 3.12. All the parameters evaluated were not significant except CP. The swede cv. American Purple Top had 214 g kg^{-1} of CP, which was significantly different compared to all other four cultivars evaluated (data not presented). Similar values of CP were reported by Teuber et al. (2009).

The analysis of variance across two environments, Carrington and Fargo in 2012, indicated the species main effect was significant for all forage root/stem quality components (Table 3.13). The species by environment interaction was only significant for ADL and IVDMD. Ash content fluctuated between 74 and 114 g kg^{-1} and CP between 102 and 173g kg^{-1}, with the highest content in kale cv. Siberian and the lowest in kale cv. Dwarf Blue Vates in both parameters (Table 3.14).

Table 3.8. Analysis of variance and mean squares of leaf quality components in two harvests combined across two environments, Carrington and Fargo, ND, in 2012.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	1	31105	608	385	11801	0.01	2279	211	25131
Rep(Env)	4	305	2998***	479	339**	147***	333**	216*	424
Sp	9	5305**‡	2065**	505	330	105**	103	214	6552**
Env x Sp	9	672	345	391	142	19	74	107	730
Env x Rep x Sp	36	152	301	212	72	16	84	71	184
Harv	1	32341	24711	3131	18951	869	195	8	23063
Env x Harv	1	14301***	9792***	30433***	18750***	1353***	17545***	20898***	31092***
Sp x Harv	9	201	1129**	285	127	69**	110	80	280
Env x Sp x Harv	9	166	161	222	115	9	171*	221**	250
Error	40	222	249	143	59	17	79	69	261
CV, %		10	9	5	5	12	1	1	2

† Env=Environment, Rep=Replicate, Sp= Species and cultivars, Harv=Harvest.
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.9. Mean forage quality of leaves (Ash, CP, and NDF) in two harvests combined across two environments, Carrington and Fargo, ND, in 2012.

	Ash			CP[¶]			NDF		
Species/cultivar	H 1	H 2	Mean	H 1	H 2	Mean	H 1	H 2	Mean
	g kg^{-1}								
Hybrids									
Winfred	164	137	150	178	174	176	248	224	236
Pacer	227	190	208	133	159	146	246	233	239
Forage rape									
Rangi	162	138	150	175	181	178	233	228	230
Barsica	149	130	140	167	181	174	217	216	216
Dwarf Essex	157	122	140	162	200	181	231	226	229
Bonar	163	133	148	166	190	178	230	235	232
W. Canola[†]									
Riley	165	132	148	162	209	186	228	224	226
Griffin	162	115	138	158	210	184	246	222	234
Athena	155	121	138	155	188	171	240	223	231
Summer	162	121	141	172	223	197	232	218	225
Mean	167	134		163	191		235	225	
LSD[‡](0.05), Sp	24						NS		
LSD (0.05), H	NS						NS		
LSD (0.05), SpxH	NS						NS		
$SpxH^1$				44					
$SpxH^2$				21					
$SpxH^3$				46					

[†] W. Canola = Winter canola, Sp = Species/cultivars, and H = Harvest.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05. Sp to compare among Sp means averaged across harvests; H to compare among harvest means averaged across Sps; SxH^1 to compare species means within a different Hs; $SpxH^2$ to compare Sp means within the same harvest, and $SpxH^3$ to compare different Hs means between different species means.

[¶] Forage quality components: Crude protein (CP) and neutral detergent fiber (NDF).

Table 3.10. Mean forage quality of leaves (ADF, ADL, and IVDMD) in two harvests combined across two environments, Carrington and Fargo, ND, in 2012.

	ADF[¶]			ADL			IVDMD		
Species/cultivar	H 1	H 2	Mean	H1	H 2	Mean	H 1	H 2	Mean
	-----------------	-----------------	-----------------	-----------------	g kg^{-1}	-----------------	-----------------	-----------------	-----------------
Hybrids									
Winfred	176	143	160	32	35	33	885	897	891
Pacer	161	137	149	44	39	42	883	890	886
Forage rape									
Rangi	169	150	160	34	35	34	886	885	886
Barsica	167	140	154	36	34	35	888	889	888
Dwarf Essex	173	143	158	38	29	34	883	886	884
Bonar	166	156	161	35	33	34	895	886	891
W. Canola[†]									
Riley	161	135	148	38	28	33	886	887	886
Griffin	164	136	150	40	29	34	884	882	883
Athena	170	141	156	40	31	36	886	894	890
Summer	159	135	147	34	25	30	880	886	883
Mean	167	141		37	32		885	888	
LSD[‡](0.05), Sp	NS						NS		
LSD (0.05), H	NS						NS		
LSD (0.05), SpxH	NS						NS		
SpxH[1]				16					
SpxH[2]				5					
SpxH[3]				16					

[†] W. Canola = Winter canola, Sp = Species/cultivar, and H = Harvests.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05. Sp to compare among Sp means averaged across harvests; H to compare among harvest means averaged across Sps; SpxH[1] to compare species means within a different Hs; SpxH[2] to compare Sp means within the same harvest, and SpxH[3] to compare different Hs means between different species means.

[¶] Forage quality components: Acid detergent fiber (ADF), acid detergent lignin (ADL), and in vitro dry matter digestibility (IVDMD).

Table 3.11. Mean forage quality of leaves (NDFD and TDN) in two harvests combined across two environments, Carrington and Fargo, ND, in 2012.

	NDFD[¶]			TDN		
Species/cultivar	H 1	H 2	Mean	H1	H 2	Mean
	----------------------------	----------------------------	-------------g kg^{-1}	----------------------------	----------------------------	----------------------------
Hybrids						
Winfred	925	930	927	756	779	767
Pacer	913	917	915	682	720	701
Forage rape						
Rangi	923	919	921	759	776	767
Barsica	932	927	929	774	787	780
Dwarf Essex	922	924	923	762	792	777
Bonar	933	923	928	760	779	769
W. Canola[†]						
Riley	924	924	924	755	781	768
Griffin	920	922	921	755	798	776
Athena	924	929	926	763	794	779
Summer	922	928	925	757	794	775
Mean	924	924		752	780	
LSD[‡](0.05), Sp	NS			25		
LSD (0.05), H	NS			NS		
LSD (0.05), SpxH	NS			NS		
SpxH[1]						
SpxH[2]						
SpxH[3]						

[†] W. Canola = Winter canola, Sp = Species, and H = Harvest.
[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05. Sp to compare among Sp means averaged across harvests; H to compare among harvest means averaged across Sps; SpxH[1] to compare species means within a different Hs; SpxH[2] to compare Sp means within the same harvest, and SpxH[3] to compare different Hs means between different species means.
[¶] Forage quality components: Neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.12. Analysis of variance and mean squares of forage quality components of leaves in two harvests combined across two environments, Carrington and Fargo, ND, in 2012.

Source of variation	Df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	1	65	2921	10944*	13739*	617	5122	5942*	1701
Rep(Env)	4	295	2611[‡]**	270	37	157**	317	187	393
Sp	4	729	3787*	1851	1636	97	2645	1984	1798
Env x Sp	4	269	440	394	878*	21	617*	356*	414
Error	16	422	426	217	184	24	146	95	437
CV, %		14	12	6	9	13	1	1	3

[†] Env=Environment, Rep=Replicate, Sp= Species and cultivars.

[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

The CP contents determined for kale, swede and hybrid in this study were similar than CP contents reported by Teuber et al. (2009). Neutral detergent fiber content fluctuated between 416 g kg^{-1} in swede cv. Major Plus and 604 g kg^{-1} in forage rape cv. Barsica. This latter cultivar had higher NDF content than all kale, swede, and winter canola cultivars, forage rape cv. Dwarf Essex, and the hybrid cv. Pacer. Acid detergent fiber fluctuated between 323 and 462 g kg^{-1} and ADL between 59 and 92g kg^{-1}. The IVDMD of root/stem fluctuated between 537 and 713 g kg^{-1} with the highest value in kale cv.Siberian and the lowest in forage rape cv. Barsica. 'Siberian' had higher IVDMD than the other two kale cultivars, the hybrid Winfred and all the forage rape cultivars with the exception of 'Dwarf Essex'. The NDFD fluctuated between 564 and 748 g kg^{-1} with the highest values in swede cultivars. 'Major Plus' was different with almost all species that produce primarily stems biomass, with the exception of kale cultivar 'Siberian'. Total digestible nutrients fluctuated between 570 and 717 g kg^{-1}, with the highest values in swede.

The analysis of variance combined across two environments, Carrington in 2013 and Fargo in 2014, for leaf, root/stem, and total forage biomass yield, leaf and root/stem total N, dead matter yield, and total biomass yield are presented in Table 3.15. The species/cultivar main effect was significant for all the parameters evaluated. The interaction between species and environment was significant for total N in roots and dead dry matter yield.

Leaf biomass yield fluctuated between 1.7 and 5.4 Mg ha^{-1}. Kale cv. Maris Kestrel had the highest yield and was different than all the others species and cultivars, with the exception of kale cv. Dwarf Blue Vates (Table 3.16). The total leaf N ranged from 71 and 169 kg N ha^{-1}, it was higher in 'Dwarf Blue Vates' and lowest in turnip cv. Purple Top. Total N will depend on soil availability and leaf yield. Any factor that reduces leaf yield will affect the total N.

Table 3.13. Analysis of variance and mean squares of forage quality components of root/stem in the last harvest combined across two environments, Carrington and Fargo, ND, in 2012.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	1	6572*‡	19141*	9858	3950	90	2242	2313	810
Rep(Env)	4	178	574	4857*	2907*	190*	4493	4201*	3399*
Sp	14	657***	1888***	20206***	11235**	625**	17051**	18137**	9957***
Env x Sp	13	80	250	3141	1848	140*	3438	3476*	1383
Error	54	126	372	1673	1001	72	1936	1616	951
CV, %		12	13	8	8	12	7	6	5

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.14. Mean forage quality of root/stem in the last harvest combined across two environments, Carrington and Fargo, ND, in 2012.

Species/cultivar	Ash	CP[¶]	NDF	ADF	ADL	IVDMD	NDFD	TDN
	----------------	----------------	----------------	----------------	g kg^{-1}	----------------	----------------	----------------
Kale								
Siberian	114	173	428	328	59	713	726	683
Maris Kestrel	86	128	513	395	77	614	648	651
D. Blue Vates[†]	74	102	522	395	74	632	642	656
Swede								
Major Plus	94	143	416	323	62	699	748	717
Am. Purple Top	102	156	421	329	64	691	740	704
Hybrids								
Winfred	87	128	571	437	87	571	593	597
Pacer	94	141	436	332	60	703	720	701
Forage Rape								
Rangi	91	134	558	427	83	587	607	604
Barsica	84	125	604	462	92	537	564	570
Dwarf Essex	99	149	489	374	70	656	674	655
Bonar	93	138	540	413	80	603	625	619
W. Canola								
Riley	109	164	449	343	63	689	702	672
Griffin	99	148	466	355	64	684	698	674
Athena	105	155	466	356	66	678	691	666
Summer	102	153	490	375	71	654	669	649
LSD[‡](0.05)	11	20	70	52	14	73	74	46
LSD[1§](0.05)	13	24	86	66	18	89	90	56

[†] D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.

[§]LSD[1] is to compare "Pacer" with other cultivars. The LSD is different because this cultivar was not in all experiments combined.

[¶] Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

The root/stem biomass yield fluctuated between 0.5 and 4.2 Mg ha^{-1}, with the highest yield in kale cv. Maris Kestrel and the lowest in the hybrid cv. Pacer. The species that produce large roots (swede and turnip) have higher root/leaf biomass yield, which is consistent with the results reported in swede in New Zealand (Gowers et al., 2006). Conversely, species with small roots but thick and large stems (kales, hybrids, forage rape, and winter canola) had a higher leaf/root ratio, hence higher total N. 'Maris Kestrel' had the highest root/stem yield than all other species and cultivars with the exception of 'Sovereign' and all swede cultivars. The total N of root/stem fluctuated between 20 and 132 kg N ha^{-1}. As in root/stem yield the kale cv. Maris Kestrel had the highest total N although not significantly different than 'Sovereign', 'Major Plus', and 'American Purple Top, all of them with more than 100 kg N ha^{-1}. The total forage biomass yield (leaf + root/stem) fluctuated between 2.2 and 9.6 Mg ha^{-1}, with 'Maris Kestrel' with the highest yield. Swede cv. Major Plus was the species with the highest yield, with 6.6 Mg ha^{-1}. Kale cv. Maris Kestrel had the highest leaf and stem total N, and total biomass yield (leaf + root/stem + dead matter), with 292 kg N ha^{-1} and 12.4 Mg ha^{-1}, respectively. Dead matter fluctuated between 2.5 and 5.0 Mg ha^{-1}, with the highest value in forage rape 'Bonar'.

The analysis of variance across two environments, Carrington 2013 and Fargo 2014, for the forage quality of leaves is presented in Table 3.17. The species/cultivar main effect was significant for all the parameters evaluated and the interaction between species and environment was significant for all parameters except for ash content and TDN.

In general, ash content was higher in species with enlarged roots than those with high proportion of stems (Table 3.18). Crude protein content fluctuated between 176 and 265 g kg^{-1}. Other species with higher CP were winter canola and swede, with averages of 250 and 254 g kg^{-1}, respectively. Several authors have reported that CP content is about 25 to 60% greater in the biomass above the soil surface than in the roots (Rao and Horn, 1986; Jung et al., 1986; Smith and Collins, 2003; Nichol et al., 2003; Villalobos and Brummer, 2013; Lemus and White, 2014). Neutral detergent fiber and ADF were the highest in two of the swede cultivars and the lowest values were found in forage rape cv. Barsica. The IVDMD and NDFD of all species was much higher than common forage species such as alfalfa (*Medicago sativa* L.) (600-750 g kg^{-1}) an indication of the high digestibility and energy content of forage brassicas. Kale cv. Sovereign had the highest IVDMD and NDFD with 914 and 943 g kg^{-1}, respectively, but it was not different from some of the other cultivars of kale, hybrids, and forage rape. Total digestible nutrient was the highest in kale and forage rape and fluctuated between 714 and 800 g kg^{-1}, respectively. Highly digestible forage requires supplementation with forages high in fiber, wheat straw, corn stover or similar materials to avoid diarrhea in cows.

The analysis of variance combined across two environments, Carrington in 2013 and Fargo in 2014, for forage quality of root/stem are presented in Table 3.19. The main effect of the species/cultivar was significant only for ash content, while all parameters were significant for the environment by species interaction. Ash content fluctuated between 72 and 115 g kg^{-1} (Table 3.20). The species with the lowest average ash content were swede and turnip with 78 and 86 g kg^{-1}, respectively. The highest ash content was determined species with small or no enlarged roots such as forage rape and winter canola.

Table 3.15. Analysis of variance and mean squares for forage brassica leaf and root biomass yield, total N, dead matter yield, and total biomass yield combined across two environments, Carrington and Fargo, ND, in 2013 and 2014, respectively.

Source of variation	df*	Leaf yield	Total leaf N	df	Root/ stem yield	Root/ stem total N	df	Leaf and root/stem yield	Total N leaf + root/stem	Dead matter yield	Total yield
Env[†]	1	115750**[‡]	320.0**	1	1960	89.0***	1	90268*	744.0***	208610***	24422
Rep(Env)	4	2857***	6.0***	4	741	1.3	4	5939**	12.6***	139	5225*
Sp	19	7197***	4.7***	19	6565***	6.7*	19	19089***	13.9***	3280**	13797***
Env x Sp	19	486	0.4	18	720	2.9***	19	1159	2.9	958***	2390
Error	76	470	0.6	74	484	0.6	76	1292	1.7	314	1731
CV, %		24	23.3		32	39.6		22	24.9	15	15

[†] Env=Environment, Rep=Replicate, S= Species and cultivars.
[‡] *, **, *** significant at 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean squares values were divided by 1000 for better fit on the table.
[¶] Total yield includes leaves, roots, and dead matter below the canopy.
* More than one column of df is due to different number of species/cultivars evaluated between leaf and root/stem yield.

Table 3.16. Mean biomass yield and total N of leaf, root/stem, and total biomass yield, dead matter, and total yield of different species/cultivars averaged across two environments, Carrington and Fargo, ND, in 2013 and 2014, respectively.

	Leaf		Root/stem		Leaf + root/stem		Dead matter	Total¶
Species/cultivar	Yield	Total N	Yield	Total N	Yield	Total N	Yield	
Kale	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	
Siberian	3.0	117	0.8	21	3.8	138	4.5	8.3
Maris Kestrel	5.4	160	4.2	132	9.6	292	2.8	12.4
D. Blue Vates†	5.3	169	1.5	38	6.7	207	2.5	9.2
Sovereign	4.3	136	3.2	104	7.5	240	2.7	10.2
Swede								
Major plus	2.7	108	3.9	101	6.6	209	3.3	10.0
Am. Purple Top	2.0	86	3.6	110	5.6	196	3.1	8.7
Dominion	2.0	82	3.1	81	5.1	163	3.1	8.2
Turnip								
Purple Top	1.7	71	2.4	80	4.1	151	3.1	7.3
Rack	2.0	84	1.8	70	3.9	154	2.9	6.8
Pointer	2.1	80	2.1	70	4.2	149	3.1	7.3
Hybrids								
Winfred	3.0	112	2.6	69	5.7	181	4.3	10.0
Pacer	2.0	75	0.5	20	2.2	85	4.3	6.4
Forage rape								
Rangi	2.6	96	2.4	55	5.1	150	4.3	9.4
Barsica	4.2	147	2.7	73	6.9	220	4.1	11.0
Dwarf Essex	2.6	105	1.4	37	4.0	143	4.3	8.3
Bonar	2.8	114	1.4	35	4.2	149	5.0	9.2
W. canola								
Riley	2.3	97	1.2	32	3.5	128	4.4	8.0
Griffin	2.4	98	0.9	26	3.3	124	4.2	7.4
Athena	2.5	104	1.1	29	3.7	132	4.3	7.9
Summer	1.9	85	1.4	41	3.4	125	3.7	7.0
LSD‡ (0.05)	0.8	25	1.0	65	1.3	65	1.2	1.9
LSD[1]§ (0.05)			1.3	80				

† D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.‡ LSD= Least significant difference used as mean separation method, with a probability of 0.05.§LSD[1] is to compare 'Pacer' with other cultivars. The LSD is different because this cultivar was not in all experiments combined.¶ Total yield includes leaves, roots, and dead matter below the canopy.

Table 3.17. Analysis of variance and mean squares of forage quality of leaves in Carrington and Fargo ND, in 2013 and 2014, respectively.

Source of variation	df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	1	496	153368***	14941	19840*	4514.0***	2823	1761	316
Rep(Env)	4	1175**[‡]	693*	4450***	1455***	36.7*	363*	509***	1988***
Sp	19	2290***	3412*	844**	732**	131.3*	1758***	1247***	3512***
Env x Sp	19	270	1154***	230*	189*	53.7***	334**	191*	287
Error	76	284	251	133	103	14.2	124	96	283
CV, %		11	7	5	6	13.2	1	1	2

[†] Env=Environment, Rep=Replicate, Sp= Species and cultivars.

[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.18. Mean forage quality of forage brassica leaves combined across two environments, Carrington and Fargo ND, in 2013 and 2014, respectively.

Species/cultivar	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
	------------------	------------------	------------------	------------------	---g kg^{-1}---	------------------	------------------	------------------
Kale								
Siberian	143	238	220	157	29.3	870	904	769
Maris Kestrel	132	176	203	167	38.3	911	942	790
D. Blue Vates[†]	124	196	194	159	37.0	905	942	800
Sovereign	129	192	214	168	35.0	914	943	792
Swede								
Major Plus	150	242	227	160	26.7	876	913	758
Am. Purple Top	155	256	237	183	25.0	850	890	751
Dominion	152	252	229	168	25.7	865	908	758
Turnip								
Purple Top	190	229	236	164	25.7	868	903	714
Rack	160	237	225	158	27.2	882	917	747
Pointer	184	221	229	155	30.2	886	918	725
Hybrids								
Winfred	133	211	219	153	30.8	904	935	783
Pacer	184	221	227	147	29.0	892	925	723
Forage rape								
Rangi	131	211	218	151	33.0	898	928	782
Barsica	133	211	193	142	31.8	906	938	787
Dwarf Essex	131	237	213	145	26.7	893	927	784
Bonar	138	241	215	148	24.8	896	933	777
W. canola								
Riley	137	249	222	146	25.0	882	919	773
Griffin	138	251	216	140	23.5	885	920	774
Athena	133	251	211	148	24.0	877	917	780
Summer	137	265	217	143	21.0	874	914	773
LSD[‡] (0.05)	20	41	18	17	9.0	22	17	21

[†] D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.

[§]Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.19. Analysis of variance and mean squares of quality variables of forage brassica root/stem combined across two environments, Carrington and Fargo ND, in 2013 and 2014, respectively.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	1	34529***‡	148898***	430070***	276169***	16488***	434010***	281719***	305941***
Rep(Env)	4	90	201	3733*	2210*	107	3164	2613	956
Sp	19	1078*	2559	11174	6455	436	10503	9942	3648
Env x Sp	19	399***	1356***	9336***	5333***	360***	8557***	8102***	1682***
Error	76	52	176	1430	868	62	1490	1287	425
CV, %		8	10	10	11	16	5	5	3

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.20. Mean forage quality of forage brassica root/stem combined across two environments, Carrington and Fargo 2013-2014.

Species/cultivar	Ash	CP[¶]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Kale				g kg^{-1}				
Siberian	112	162	296	227	34.2	831	834	756
Maris Kestrel	96	132	372	285	51.0	752	757	725
D. Blue Vates[†]	90	119	376	286	49.7	757	756	733
Sovereign	83	109	443	339	64.2	684	685	689
Swede								
Major Plus	74	104	302	233	37.2	808	820	780
Am. Purple top	72	100	320	248	39.8	793	806	772
Dominion	87	125	309	240	40.3	795	806	764
Turnip								
Purple Top	88	137	348	272	48.2	756	781	747
Rack	85	131	415	323	61.5	690	715	702
Pointer	86	133	391	305	57.2	712	738	721
Hybrids								
Winfred	98	136	383	292	50.7	753	755	722
Pacer	81	127	439	337	60.9	689	707	698
Forage rape								
Rangi	100	139	363	278	47.8	767	768	731
Barsica	89	118	440	336	62.7	692	695	690
Dwarf Essex	104	147	377	289	49.8	756	758	720
Bonar	117	169	338	260	44.2	788	793	730
W. Canola								
Riley	109	159	322	246	38.8	808	814	748
Griffin	112	164	356	273	46.3	771	780	725
Athena	115	168	350	269	45.0	780	785	724
Summer	98	137	371	284	48.3	760	765	731
LSD[‡] (0.05)	24	NS	NS	NS	NS	NS	NS	NS
LSD[1§] (0.05)	30	NS	NS	NS	NS	NS	NS	NS

[†] D. Blue Vates = Dwarf Blue Vates, Am. Purple Top = American Purple Top, W. canola = Winter canola.
[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.
[§]LSD[1] is to compare 'Pacer' with other cultivars. The LSD is different because this cultivar was not in all experiments combined.
[¶]Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN)

3.4.3. Sowing date experiment

The analysis of variance combined across four environments, Fargo and Prosper in 2012 and 2014, for leaf, root/stem, leaf + root/stem, dead matter, and total biomass yield, and total N of the biomass yield are presented in Table 3.21. The species and sowing date (SD) interaction was significant for all parameters evaluated except dead matter, leaf total N, and total forage N. The species main effect was significant for all the parameters evaluated, and sowing date main effect was significant for all parameters except leaf yield, leaf total N, and total forage N.

The mean leaf biomass yield was higher in kale, compared with swede, winter canola, and turnip (Table 3.22). In general, the leaf yield decreased as sowing date was delayed. Similarly, Harper and Compton (1980), reported that 'Maris Kestrel' was the most sensitive crop to a delayed sowing date causing yield to decline. 'Maris Kestrel' had always the highest leaf yield across all sowing dates, but differences among crops decreased as the sowing date was delayed.

Mean root/stem yield was always higher in the first sowing date in all species decreasing as sowing date was delayed. The highest root/stem yield was observed in swede cv. Major Plus, followed by kale, turnip, and winter canola. The highest yield was obtained by swede cv. Major Plus with 7.9, 5.0, and 3.4 Mg ha^{-1}, in SD1, SD2, and SD3, respectively, being significantly different with all other species/cultivars in each sowing date. A higher root and stem yield than leaf yield suggests that some brassica species can translocate assimilates from the leaves to roots and stems in the cool, fall conditions and thus continue accumulating dry matter (Harper and Compton, 1980). Mean biomass yield of turnip and kale were different than winter canola in almost all sowing dates, except SD3.

The total forage biomass yield has a similar trend than root/stem biomass yield (Table 3.22). The highest yields were obtained in swede cv. Major Plus in the first sowing date and as observed for leaf and root yield differences between species decreased as the sowing date was delayed. Yield was higher in earlier sowing dates likely because of greater accumulated thermal time in the season (Brown et al., 2007). The leaf total N and total biomass yield (leaf + root/stem) was different only species for the species main effect (Table 3.23). Kale had highest total N leaf across sowing dates (96 kg N ha^{-1}). The leaf + root/stem total N was highest in swede cv. Major Plus with 178 kg N ha^{-1}. The root/stem total N was higher in swede in the first sowing date. The total N decreased as sowing dates were delayed. Swede cv. Major Plus had a total N of 130 kg N ha^{-1}, the highest root/stem total N of all species and cultivars in the first date. Similarly, as in total root and leaf yield, total N differences among species also decreased as sowing dates were delayed. The dead matter (dead plants or part of them found under canopy) yield biomass was different for species and sowing date main effects (Table 3.24). The SD2 and SD3 had the lowest dead matter with 3.2 and 2.3 Mg ha^{-1}. Kale had the lowest dead matter yield with only 2.7 Mg ha^{-1}. The total biomass yield (leaf + root/stem + dead matter) was higher in swede and kale, and higher in SD1 compared with SD2 and SD3. The swede cv. Major Plus had the highest total biomass yield with 17.5 Mg ha^{-1} in SD1, which was different with all species except kale. The total N in leaves and total forage biomass yield (leaf+ root/stem) was different only for the species main effect (Table 3.21). Kale had highest total leaf N across sowing dates (96 kg N ha^{-1}). The leaf+ root/stem total N was highest in swede cv. Major Plus with 178 kg N ha^{-1}. The root/stem total N was higher in swede in the first sowing date. The total N decreased as sowing dates were delayed. Swede cv. Major Plus had a total N of 130 kg N ha^{-1}, the highest root/stem total N of all species and cultivars in the first sowing date. Similarly, as in total root/stem and leaf yield, total N differences among species also decreased as sowing dates were delayed. The dead matter (dead plants or part of them found under canopy) yield biomass was different for species and sowing date main effects (Table 3.24). The SD2 and SD3 had the lowest dead matter with 3.2 and 2.3 Mg ha^{-1}. Kale had the lowest dead matter yield with only 2.7 Mg ha^{-1}. The total biomass yield (leaf+ root/stem + dead matter) was higher in swede and kale, and higher in SD1 compared with SD2 and SD3. The swede cv. Major Plus had the highest total biomass yield with 17.5 Mg ha^{-1} in SD1, which was different with all species except kale. This highest yield was different between all species in SD2 and SD3.

The leaf N accumulations and Nin total biomass yield (leaf + root/stem) was different only species for the species main effect (Table 3.23). Kale had highest total N of leaf across sowing dates (96 kg N ha^{-1}). The root/stem total N was higher in swede in the first sowing date. The total forage N decreased as sowing dates were delayed. Swede cv. Major Plus had a total N of 130 kg N ha^{-1}, the highest root/stem total N of all species and cultivars in the first sowing date. Similarly, as in total root/stem and leaf yield, total N differences among species also decreased as sowing dates were delayed. The dead matter (dead plants or part of them found under canopy) yield biomass was different for species and sowing date main effects (Table 3.24). The SD2 and SD3 had the lowest dead matter with 3.2 and 2.3 Mg ha^{-1}. Kale had the lowest dead matter yield with only 2.7 Mg ha^{-1}. The total biomass yield (leaf + root/stem + dead matter) was higher in swede and kale, and higher in SD1 compared with SD2 and SD3. The swede cv. Major Plus had the highest total biomass yield with 17.5 Mg ha^{-1} in SD1, which was different with all species except kale. This highest yield was different between all species in SD2 and SD3. The analysis of variance combined across four environments, Fargo and Prosper in 2012 and 2014, for forage leaf quality components are presented in Table 3.25. The SD main effect and the species x SD interaction were not significant for all components evaluated. The species main effect was significant for all components except ADF, ADL, and NDFD.

The leaf ash content was higher in turnip and lowest in kale (Table 3.26). The CP content was higher in winter canola leaves. In most species, CP content increased as sowing date was delayed similarly to that reported by Kunelius et al. (1987), Nichol et al. (2003), Teuber et al. (2009) and Tiryakioglu and Turk (2012) (Table 3.26). In most species, NDF decreased when sowing date was delayed. A similar response was reported by Tiryakioglu and Turk (2012). The IVDMD and TDN behave similarly and did not change with later sowing dates (Table 3.27 and 3.28), which is according with the results reported by Jung et al. (1986) and Kunelius et al. (1987).

The analysis of variance for forage root/stem quality components, combined across four environments, Fargo and Prosper in 2012 and 2014, are presented in Table 3.29. The SD main effect and the species x SD interaction were not significant for all components evaluated. The species main effect was significant only for ash and CP components. Winter canola had higher ash content, significantly different with kale and swede but similar with turnip (Table 3.30). Turnip ash content was also significantly higher than swede ash content. The CP trend was similar than the ash content. Also, all species evaluated increased in CP content when the SDs were delayed, which was consistent with the results reported by Nichol et al. (2003), Turk et al. (2009), and Tiryakioglu and Turk (2012). The rest of root/stem quality paramerts were no significantly different (Table 3.31 and 3.32).

Table 3.21. Analysis of variance and mean squares for forage brassica leaf, root/stem, leaf + root/stem, dead matter, and total biomass yield, and total N of forage biomass yield for forage brassica sowing date (SD) in four environments, Fargo and Prosper ND, 2012 and 2014.

Source of variation	df	Leaf yield	Root/ stem yield	Leaf and root/stem yield	Dead matter yield	Total biomass yield	Leaf total N	Root/ stem total N	Total N
Env[†]	3	58741**[‡§]	56234**	171808**	18763	206542**	38.26*	8.9*	78.2**
Rep(Env)	8	1407	1602	4049	735	3408	1.20	0.5	2.5
SD	2	1240	35529*	49722*	64112*	225999**	0.03	8.6*	7.6
Env x SD	4	968	3364	4875	6187*	9983	1.18	0.6	2.8
Env x SD x Rep	12	657	2141*	2417	1591***	6118*	1.41	0.6	1.6
Sp	3	30788*	71340***	111441**	9324*	80391*	9.25*	16.5***	23.8*
Env x Sp	9	5403**	2271*	10169**	2184*	15848**	2.20	1.1*	4.0
SD x Sp	6	2122*	5927***	11462**	759	16037**	0.77	1.5**	3.1
Env x SD x Sp	12	726	605	1836	743	3049	0.96	0.3	2.1
Error	60	767	1020	2540	420	3181	0.77	0.4	1.8
CV, %		28	35	26	20	19	35.40	38.9	32.4

[†] Env=Environment, Rep=Replicate, Sp= Species and cultivars.
[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean squares values were divided by 1000 for better fit on the table.

Table 3.22. Mean biomass yield of forage brassica leaf, root/stem and leaf + root/stem in four species and three sowing dates (SD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Leaf yield				Root/stem yield				Leaf + root/stem yield			
Species	SD1§	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	----------	----------	----------	----------	----------	----------	$Mg\ ha^{-1}$	----------	----------	----------	----------	----------
Turnip	2.1	1.8	2.2	2.0	4.2	3.4	2.8	3.5	6.3	5.2	5.0	5.5
Kale	5.5	4.5	3.8	4.6	4.3	3.1	1.9	3.1	9.8	7.6	5.7	7.7
Swede	4.0	3.1	3.4	3.5	7.9	5.0	3.4	5.4	11.9	8.1	6.7	8.9
W. canola†	2.4	3.3	2.9	2.9	1.4	1.5	1.0	1.3	3.8	4.8	4.0	4.2
Mean	3.5	3.2	3.1		4.4	3.2	2.3		8.0	6.4	5.3	
LSD‡ (0.05), SD												
LSD (0.05), Sp												
LSD (0.05), SDxS												
SDxSp[1]	1.7¶	1.5			1.3	1.0			2.5	2.1		
SDxSp[2]	1.0	0.8			1.3	1.0			1.9	1.4		
SDxSp[3]	1.6	1.5			1.5	1.3			2.5	2.2		

† W. canola = Winter canola.

‡ LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp[1] to compare species means within a same SDs; SDxSp[2] to compare SD means within the same species, and SDxSp[3] to compare different SDs means between different species means.

§ Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

¶ LSD under column SD1 are to compare SD1 means with SD2 or SD3. LSD under column SD2/SD3 are to compare SD2 or SD3, due to different number of observations in SD1 vs SD2/SD3 to determine LSDs.

Table 3.23. Mean forage brassica leaf, root/stem, and leaf + root/stem yield and total N in four species and three sowing dates (SD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Total leaf N				Total root/stem N				Leaf+ root/stem N			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	----------kg ha^{-1}----------											
Turnip	51	52	61	55	87	69	57	71	136	121	118	125
Kale	102	99	85	96	69	50	39	53	172	149	125	149
Swede	98	83	99	93	130	67	56	84	230	151	155	178
W. canola[†]	67	89	83	80	25	28	22	25	93	117	105	105
Mean	80	81	82		78	53	43		158	134	125	
LSD[‡] (0.05), SD	NS				NS				NS			
LSD (0.05), Sp	29				NS				39			
LSD (0.05), SDxS	NS								NS			
SDxSp[1]					29[¶]	23						
SDxSp[2]					23	17						
SDxSp[3]					28	24						

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance: SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp[1] to compare species means within a same SDs; SDxSp[2] to compare SD means within the same species, and SDxSp[3] to compare different SDs means between different species means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

[¶] LSD under column SD1 are to compare SD1 means with SD2 or SD3. LSD under column SD2/SD3 are to compare SD2 or SD3, due to different number of observations in SD1 vs SD2/SD3 to determine LSDs.

Table 3.24. Mean biomass yield of forage brassica dead matter and total biomass yield in four species and three sowing dates (SD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Dead matter				Total biomass yield			
Species†	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	-----------------------------------	-----------------------------------	-----------------------------------	------------------------$Mg\ ha^{-1}$	-----------------------------------	-----------------------------------	-----------------------------------	-----------------------------------
Turnip	5.1	3.4	2.6	3.7	11.5	8.7	7.6	9.3
Kale	4.5	2.4	1.3	2.7	14.5	9.9	7.0	10.5
Swede	5.4	3.0	2.4	3.6	17.5	11.1	9.1	12.6
W. canola	5.4	4.1	2.7	4.1	9.3	8.9	6.7	8.3
Mean	5.1	3.2	2.3		13.2	9.7	7.6	
LSD[‡] (0.05), SD	1.8				NS			
LSD (0.05), Sp	0.9				NS			
LSD (0.05), SDxS	NS							
SDxSp[1]					3.2[¶]	2.6		
SDxSp[2]					2.5	1.9		
SDxSp[3]					3.3	2.9		

† W. canola = Winter canola.

‡ LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp[1] to compare species means within a same SDs; SDxSp[2] to compare SD means within the same species, and SDxSp[3] to compare different SDs means between different species means.

§ Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

LSD under column SD1 are to compare SD1 means with SD2 or SD3. LSD under column SD2/SD3 are to compare SD2 or SD3, due to different number of observations in SD1 vs SD2/SD3 to determine LSDs.

Table 3.25. Analysis of variance and mean squares of forage quality components of leaves of forage brassica sowing date (SD) in Fargo and Prosper ND, 2012 and 2014.

Source of variation	df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	3	17129**[‡]	23066*	31521**	1608	278	11728**	13427**	27806**
Rep(Env)	8	450	1006	837***	576**	94	65	22	708
SD	2	332	2399	1174	876	220	12	81	151
Env x SD	4	455	760	595	388	74	195	132	404
Env x SD x Rep	12	404	1480***	104	116	77**	167**	102	458
Sp	3	18119***	17285*	10294*	2481	566	6619*	3892	31353***
Env x Sp	9	1232*	2864*	2447**	1638***	172*	1442***	1302***	1989**
SD x Sp	6	144	642	496	219	46	118	152	217
Env x SD x Sp	12	355	779*	346	146	62**	67	53	420
Error	60	291	350	441	254	24	65	61	399
CV, %		11	12	9	10	12	1	1	3

† Env=Environment, Rep=Replicate, Sp= species and cultivars.
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.26. Mean forage quality (Ash, CP and NDF) of forage brassica leaves with four species and three sowing dates (SD) combined across all environments, Fargo and Prosper ND, in 2012 and 2014.

	Ash				CP				NDF			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	------------------------------g kg^{-1}------------------------------											
Turnip	189	181	182	184	151	168	174	164	279	276	259	271
Kale	120	130	132	127	112	134	138	128	235	221	227	228
Swede	142	144	148	144	158	172	191	173	251	233	227	237
W. canola[†]	129	127	139	132	194	183	187	188	247	239	245	244
Mean	145	146	150		153	164	173		253	242	239	
LSD[‡] (0.05), SD	NS				NS				NS			
LSD (0.05), Sp	22				33				30			
LSD (0.05), SDxSp	NS				NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

Table 3.27. Mean forage quality (ADF, ADL, and IVDMD) of forage brassica leaves with four speciess and three sowing dates (SD) combined across all environments in Fargo and Prosper ND, in 2012 and 2014.

	ADF				ADL				IVDMD			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	---g kg^{-1}	---										
Turnip	169	173	160	167	46	40	38	42	870	863	870	868
Kale	178	166	169	171	52	46	44	47	904	905	904	904
Swede	167	154	149	156	44	38	34	39	878	887	883	883
W. canola[†]	154	152	149	152	35	38	37	37	884	887	884	885
Mean	167	161	157		44	40	38		884	886	885	
LSD[‡] (0.05), SD	NS				NS				NS			
LSD (0.05), Sp	NS				NS				23			
LSD (0.05), SDxSp	NS				NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

Table 3.28. Mean forage quality (NDFD and TDN) of forage brassica leaves with four species and three sowing dates (SD) combined across all environments in Fargo and Prosper ND, in 2012 and 2014.

	NDFD				TDN			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	----------	----------	----------	---------- g kg^{-1}	----------	----------	----------	----------
Turnip	904	898	908	903	706	713	717	712
Kale	928	933	932	931	795	789	785	789
Swede	912	921	919	918	764	766	764	765
W. canola[†]	921	922	919	921	779	781	769	776
Mean	916	918	920		761	762	759	
LSD[‡] (0.05), SD	NS				NS			
LSD (0.05), Sp	NS				27			
LSD (0.05), SDxSp	NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

Table 3.29. Analysis of variance and mean squares of forage quality components of brassica root/stem for forage brassica sowing date (SD) combined across four environments, Fargo and Prosper ND, 2012 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	3	3082*‡	15507*	464144***	278971***	17404***	452007***	310908***	120896***
Rep(Env)	8	33	71	456	269	19	439	449	249
SD	2	1145	3051	3552	1987	90	3172	2524	30
Env x SD	4	241	641	958	580	41	1283	1001	317
Env x SD x Rep	12	126	413	707	407	33	775	813	243
Sp	3	3420**	11101**	9013	4777	263	6890	9002	3858
Env x Sp	9	445*	1467*	12256***	6865***	383***	8020***	8049***	3402***
SD x Sp	6	106	363	856	544	56	1117	1074	483
Env x SD x Sp	12	120	417	595	364	27	662	533	325
Error	60	86	241	777	458	35	818	791	330
CV, %		11	12	8	8	12	4	4	3

† Env=Environment, Rep=Replicate, Sp= Species and cultivars

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.30. Mean forage quality (Ash, CP, and NDF) of forage brassica root/stem with four species and three sowing dates (SD) in Fargo and Prosper ND, in 2012 and 2014, and combined across all environments.

	Ash				CP				NDF			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	--g kg^{-1}--											
Species												
Turnip	90	90	92	91	131	132	134	132	331	323	310	322
Kale	72	83	93	82	92	110	128	110	358	368	344	357
Swede	70	72	80	74	94	95	109	99	333	306	316	318
W. canola[†]	96	98	107	100	137	139	155	144	332	320	299	317
Mean	82	86	93		114	119	131		339	329	317	
LSD[‡] (0.05), SD	NS				NS				NS			
LSD (0.05), Sp	13				24				NS			
LSD (0.05), SDxSp	NS				NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

Table 3.31. Mean forage quality (ADF, ADL, and IVDMD) of forage brassica root/stem with four speciess and three sowing dates (SD) in Fargo and Prosper ND, in 2012 and 2014, and combined across all environments.

	ADF				ADL				IVDMD			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	----------g kg^{-1}----------											
Turnip	258	251	241	250	45.1	43.3	41.1	43.2	779	788	801	789
Kale	273	281	263	272	47.2	49.8	45.4	47.5	768	758	781	769
Swede	256	235	244	245	43.7	38.3	42.3	41.5	785	811	796	797
W. canola[†]	254	245	229	243	43.6	41.3	36.8	40.5	790	801	825	806
Mean	260	253	244		44.9	43.2	41.4		780	790	801	
LSD[‡] (0.05), SD	NS				NS				NS			
LSD (0.05), Sp	NS				NS				NS			
LSD (0.05), SDxSp	NS				NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

Table 3.32. Mean forage quality (NDFD and TDN) of forage brassica root/stem with four species and three sowing dates (SD) in Fargo and Prosper ND, in 2012 and 2014, and combined across all environments.

	NDFD				TDN			
Species	SD1[§]	SD2	SD3	Mean	SD1	SD2	SD3	Mean
	----	----	----	----	$g\ kg^{-1}$	----	----	----
Turnip	799	804	815	806	743	746	752	747
Kale	770	760	783	771	756	738	743	746
Swede	799	824	809	810	765	778	766	770
W. canola[†]	793	803	825	807	738	746	750	745
Mean	790	798	808		751	752	753	
LSD[‡] (0.05), SD	NS				NS			
LSD (0.05), Sp	NS				NS			
LSD (0.05), SDxSp	NS				NS			

[†] W. canola = Winter canola.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1 = May 1; SD2 = May 15; SD3 = May 30.

3.4.4. Forage brassica and plant density effect

The analysis of variance combined across four environments, Fargo and Prosper in 2012 and 2014, for leaf, root/stem, leaf + root/stem, dead matter, total biomass yield, and total N of the biomass yield are presented in Table 3.33. The plant density (PD) main effect was not significant for all parameters evaluated. The species x PD interaction was significant for root/stem biomass yield and root/stem total N. The species main effect was significant for all the parameters evaluated except leaf yield, total biomass and leaf total N. In leaf biomass yield, leaf total N and total biomass yield, no significant differences in main effects nor interaction were found.

Leaf biomass yield and total N did not show differences between PDs, species and the interaction PD x species (Table 3.34). Root/stem biomass yield had differences between species across PDs (Table 3.35). The highest root/stem biomass yield was in swede cv. Major Plus with 5.6 Mg ha^{-1} in PD1 and 5.4 Mg ha^{-1} in PD3, which was different from kale and forge rape within the same PD. Swedes highest yields were observes in PD1 and PD3. Kale and forage rape did not have differences in yield when different PDs were compared. These results agree with Stefanski et al. (2010) which did not found differences in forage rape yield across different PDs. However, this did not agree with Sharaan and Abdel-Gawad (1986), who found differences in forage rape yield, when higher PDs were evaluated. According to Stefanski et al. (2010), forage rape has the ability to adjust to increasing competition for resources while maintaining yield when grown at low PDs. The null effect of PD on biomass yield could be explained by the scarce differences in the final PD observed in the field at harvest time, which was different that the targeted PDs at the beginning of the season (Table 3.38). These scarce differences could be explained by self-thinning during the later stages of development after emergence, particularly in high PDs (Almond et al., 1986; Bilgili et al., 2003). Also, the losses of seedlings and plants could be caused by intra-competition for soil moisture at the heavier sowing rates (Gramshaw and Crofts, 1969).

The total N of root/stem was higher in swede, followed by kale and forage rape across all PDs (Table 3.35). Also, differences among plant densities were observed only in swedes. Finally, all the swede PD were different from forage rape root/stem, but only swede biomass yield in PD1 was different with all kale PD root/stem yields.

The total forage biomass (leaf+ root/stem) yield was higher in swede, which was different from forage rape (Table 3.36). This result agrees with Stefanski et al. (2010) who did not find differences between different PDs, working with forage rape. However, they used sowing rates between 2 and 5 kg ha^{-1} to find differences in plant densities, but this sowing rate range could be too narrow to find differences. Conversely, Sharaan and Abdel-Gaward (1986) used sowing rates up to 21.5 kg of forage rape finding differences among densities. In kale, the total yield increase was small over a wide range of densities above 15 plants m^{-2} (Harper and Compton, 1980). Also, Cho et al. (1998) found higher forage rape biomass yield with sowing rates greater than 9 kg ha^{-1}. Forage rape densities from 14 to 214 plants m^{-2} had different biomass yields (Gramshaw and Crofts, 1969). The leaf+ root/stem total N had the same trend than the leaf + root/stem yield, with the highest total N in swede, which was different from forage rape but not with kale. Dead matter was higher for forage rape, probably because these species are mature earlier than swede and kale, thus the leaves senesce and die (Table 3.37). Plant density did not affect dead matter and total biomass production.

Table 3.33. Analysis of variance and mean squares for forage brassica leaf, root/stem, leaf + root/stem, dead matter, and total biomass yield, and total leaf, root/stem total N and total forage biomass yield for forage brassica plant density (PD) in Fargo and Prosper ND, 2012 and 2014.

Source of variation	df	Leaf yield§	Root/stem yield	Leaf and root/stem yield	Dead matter yield	Total biomass yield	Leaf N	Root/ stem N	Total N ¶
Env†	3	103602**‡	110692*	188321*	96678**	394349*	73.0***	15.0	126.0***
Rep(Env)	8	429	965	1342	4072**	8589	0.5	0.5	1.0
PD	4	665	1300	2502	1046	5761	1.0	0.5	1.6
Env x PD	12	1556	936	3177	1525	6515	2.0*	0.2	2.8
Env x PD x Rep	32	759	870	2444	1124	4362	0.7	0.3	1.5
Sp	2	45085	144163*	253048*	88370***	117416	2.7	33.1*	52.5*
Env x Sp	6	9187***	13451***	35734***	2540	45794***	3.5***	4.1***	6.***
PD x Sp	8	654	2922**	3877	1916	8194	0.4	0.7*	1.1
Env x PD x Sp	24	465	749	1676	2279**	4025	0.3	0.2	0.7
Error	80	606	934	2349	961	4511	0.5	0.3	1.2
CV, %		28	30	26	21	20	34.0	33.6	29.4

† Env=Environment, Rep=Replicate, Sp= species and cultivars.
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Mean squares values were divided by 1000 for better fit on the table.
¶ Total forage N = Total N of leaf + root/stem biomass.

Table 3.34. Mean leaf biomass yield and total leaf N of forage brassica with three species and five plant densities (PD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Leaf yield						Total leaf N					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	------------------------Mg ha^{-1}---------------------						-------------------------kg ha^{-1}----------------------					
Kale	3.5	3.7	3.7	3.8	3.7	3.7	69	75	70	71	78	72
Swede	2.7	2.6	2.7	2.3	3.1	2.7	69	69	74	64	86	72
F. rape[†]	2.3	1.9	1.9	1.7	2.1	2.0	73	54	59	51	66	61
Mean	2.8	2.7	2.8	2.6	3.0		70	66	68	62	77	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	NS						NS					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.35. Mean root/stem biomass yield and total root/stem N of forage brassica with three speciess and five plant densities (PD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Root/stem yield						Total root/stem N					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	-------------------------Mg ha^{-1}----------------------						--------------------------kg ha^{-1}-----------------------					
Kale	3.0	3.2	3.2	3.4	3.0	3.2	54	57	50	55	47	53
Swede	5.6	4.4	5.4	4.0	4.4	4.8	87	70	83	60	67	73
F. rape[†]	1.4	1.4	1.8	1.9	2.0	1.7	25	23	28	27	30	27
Mean	3.3	3.0	3.5	3.1	3.1		56	50	54	47	48	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	NS						NS					
LSD (0.05), PDxSp												
PDxSp[1]	1.5						27					
PDxSp[2]	0.8						13					
PDxSp[3]	1.5						27					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means. PDxSp[1] to compare species means within a same PDs; PDxSp[2] to compare PD means within the same species, and Sp to compare different PDs means between different species means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.36. Mean leaf plus root/stem biomass yield and total forage N of forage brassica with three species and five plant densities (PD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Leaf+ root/stem yield						Leaf + root/stem N					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	------------------------Mg ha^{-1}---------------------						-------------------------kg ha^{-1}----------------------					
Kale	6.4	6.9	6.9	7.2	6.8	6.8	123	132	120	126	125	125
Swede	8.3	7.0	8.2	6.3	7.5	7.5	156	138	156	124	153	145
F. rape[†]	3.7	3.2	3.7	3.5	4.0	3.6	98	76	87	78	96	87
Mean	6.1	5.7	6.2	5.7	6.1		126	115	121	110	125	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	2.7						35					
LSD (0.05), PDxSp	NS						NS					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.37. Mean dead matter and total biomass yield of forage brassica with three species and five plant densities (PD) averaged across four environments, Fargo and Prosper ND, in 2012 and 2014.

	Dead matter						Total biomass yield					
	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	-------------------------Mg ha^{-1}----------------------						-------------------------Mg ha^{-1}-----------------------					
Species												
Kale	3.5	3.8	3.5	3.6	3.0	3.5	9.9	10.7	10.4	10.8	9.7	10.3
Swede	4.7	4.8	5.3	4.5	4.6	4.8	13.1	11.8	13.4	10.8	12.1	12.3
F. rape[†]	6.2	5.1	6.2	5.8	6.3	5.9	9.9	8.3	9.8	9.4	10.3	9.5
Mean	4.8	4.6	5.0	4.7	4.6		11.0	10.3	11.2	10.3	10.7	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	0.7						NS					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.38. Final plant density of forage brassicas at harvest time at Fargo and Prosper, ND, in 2012, and 2014.

Species/cultivar	PD1[†]	PD2	PD3	PD4	PD5
	--plants m^{-2}	--			
Forage rape	25	30	41	50	68
Kale	24	26	34	46	59
Swede	21	25	30	34	48

[†] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

The analysis of variance for forage quality components in forage brassica leaves, combined across four environments for Fargo and Prosper in 2012 and 2014, are presented in Table 3.39. The PD main effect was significant only for IVDMD and NDFD. The species main effect was significant for all forage quality parameters, but the interaction was not significant for any components evaluated.

The ash content and CP were not affected by PDs and a few differences were observed among species (Table 3.40). However, Cho et al. (1998) did find differences among PDs on ash content and CP in forage rape leaves while increased linearly with increasing sowing rates. The ADF and ADL content were lower in swede and forage rape (Table 3.41 and 3.42). The fiber content was not affected by PDs, however, Cho et al. (1998) reported that fiber content in leaves decreased as sowing rates increased from 3 to 15 kg ha^{-1}. The IVDMD content was significantly higher in PD2, compared with PD5 which could be explained by the increased stem/leaf ratio due to competition. Neutral detergent fiber digestibility was higher for kale and lower for PD5 compared with the other four PD´s (Table 3.43).

Table 3.39. Analysis of variance and mean squares of forage quality components of leaves in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	3	32115***‡	52628**	51151***	9242**	1188*	13632**	18851***	42384***
Rep(Env)	8	433	371	231	124	24	208	300*	515
PD	4	625	353	417	113	13	538**	321*	906
Env x PD	12	324	285	321	83	22	78	60	396
Env x PD x Rep	32	256	557**	223	152*	33**	112*	100	329
Sp	2	11603**	70077***	7872*	4269*	2497**	11204*	5886**	21275**
Env x Sp	6	965*	2179***	1303**	626***	191***	1259***	465**	1124
PD x Sp	8	255	232	117	51	13	85	68	271
Env x PD x Sp	24	349	386	349*	111	23	114*	120*	476
Error	80	279	280	207	89	17	68	63	339
CV, %		12	10	6	6	10	1	1	2

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.40. Mean forage quality (Ash and CP) of forage brassica leaves in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	Ash						CP					
Species	PD1§	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	$g\ kg^{-1}$											
Kale	136	130	134	126	134	132	126	131	124	125	131	127
Swede	158	147	163	145	158	154	171	166	170	177	173	171
F. rape†	124	128	127	127	135	128	190	187	196	197	204	195
Mean	139	135	141	133	142		162	161	163	166	169	
LSD‡ (0.05), PD	NS						NS					
LSD (0.05), Sp	14						21					
LSD (0.05), PDxSp	NS						NS					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.41. Mean forage quality (NDF and ADF) of forage brassica leaves with three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	NDF						ADF					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	$g\ kg^{-1}$											
Kale	235	231	232	226	232	231	177	175	176	176	179	176
Swede	251	253	259	246	257	253	161	161	161	161	162	161
F. rape[†]	246	250	245	243	253	247	160	164	163	158	169	163
Mean	244	245	246	238	247		166	167	167	165	170	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	16						11					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.42. Mean forage quality (ADL and IVDMD) of forage brassica leaves with three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	ADL						IVDMD					
Species	PD1§	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	--------------------						g kg^{-1}	--------------------				
Kale	48.1	46.8	48.2	48.7	47.6	47.9	903	906	902	904	897	902
Swede	40.5	41.2	39.8	38.8	39.9	40.1	879	883	879	880	877	880
F. rape†	36.1	36.8	35.1	33.8	33.7	35.1	882	882	879	880	867	878
Mean	41.6	41.6	41.0	40.4	40.4		888	890	886	888	880	
LSD‡ (0.05), PD	NS						5					
LSD (0.05), Sp	6.2						16					
LSD (0.05), PDxSp	NS						NS					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.43. Mean forage quality (NDFD and TDN) of forage brassica leaves with three speciess and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	NDFD						TDN					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	$g\ kg^{-1}$											
Kale	930	933	930	933	928	931	779	786	782	791	782	784
Swede	911	915	913	913	910	912	746	757	741	760	744	749
F. rape[†]	918	919	916	920	907	916	785	780	780	783	771	780
Mean	920	922	920	922	915		770	774	768	778	766	
LSD[‡] (0.05), PD	4						NS					
LSD (0.05), Sp	10						15					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

The analysis of variance for forage quality components in forage brassica root/stem, combined across four environments for Fargo and Prosper in 2012 and 2014, are presented in Table 3.44. The interaction of species x PD was not significant. The PD main effect was significant for all components except ash, CP, and TDN and the species main effect was significant for all components except CP.

The ash content in forage root/stem was higher in forage rape, which was significantly higher than swede but similar to kale (Table 3.45). Other studies have found differences in ash content of root of forage rape as sowing rates varies (Cho et al., 1998). The NDF, ADF, and ADL were higher in forage rape (Table 3.46 and 3.47). Additionally, PD5 was significantly higher than PD1 and PD2 for NDF, ADF and ADL which makes sense, because higher densities would cause plants to etiolate, producing longer stems likely with more cellulose, hemicellulose and lignin. It is known plants under competition deposit more cellulose, hemicellulose and lignin in the cell wall to stand competition (Liu et al., 2016). The IVDMD and NDFD were higher in swede, respectively, which were different than kale and forage rape (Table 3.47 and 3.48). The IVDMD and NDFD in PD1 were significantly higher than PD3, PD4, and PD5. Sowing rate may influence the plant architecture, including plant height, height of the apical growing points and leaf to stem ratio modifying the cell wall components and digestibility of the forage (Fulkerson, 2008).

Table 3.44. Analysis of variance and mean squares of forage quality components of brassica root/stem in three species and five plant densities (PD) in Fargo and Prosper ND, 2012 and 2014.

Source of variation	df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	3	2509*[‡]	20682*	912684***	547774***	32517***	864435***	593059***	325081***
Rep(Env)	8	126	409	3131	1756	102	2482	2580	1073
PD	4	711	1514	14526*	8100*	468*	12483*	10869*	3118
Env x PD	12	324	778	3063	1788	121	3350	2826	1207
Env x PD x Rep	32	78	229	1451	825	54	1331	1205	494
Sp	2	2687*	7246	282539**	158279**	9441**	220427**	249989**	129123***
Env x Sp	6	416	2687***	16952**	9470**	757**	14766*	15406**	2235
PD x Sp	8	232	406	8629	5114	303	7868	6448	3791
Env x PD x Sp	24	174***	429**	4194***	2426***	165***	4137***	3573***	1773***
Error	80	55	169	1391	810	60	1470	1385	539
CV, %		9	12	10	10	15	5	5	3

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.45. Mean forage quality (Ash and CP) of forage brassica root/stem in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	Ash						CP					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	$g\ kg^{-1}$											
Kale	84	86	76	77	77	80	114	115	99	102	101	106
Swede	74	73	73	73	73	73	99	100	99	99	98	99
F. rape[†]	97	94	84	77	79	86	136	130	118	110	111	121
Mean	85	84	78	76	76		116	115	105	103	103	
LSD[‡] (0.05), PD	NS						NS					
LSD (0.05), Sp	9						NS					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.46. Mean forage quality (NDF and ADF) of forage brassica root/stem in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	NDF						ADF					
Species	PD1§	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	--g kg^{-1}--											
Kale	386	386	382	383	392	386	295	295	291	292	299	294
Swede	304	288	317	315	323	309	234	223	244	242	248	238
F. rape†	375	418	465	494	481	446	286	319	355	377	367	341
Mean	355	364	388	397	399		272	279	297	303	305	
LSD‡ (0.05), PD	28						22					
LSD (0.05), Sp	58						44					
LSD (0.05), PDxSp	NS						NS					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.47. Mean forage quality (ADL and IVDMD) of forage brassica root/stem in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	ADL						IVDMD					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	---g kg^{-1}---											
Kale	52.3	53.3	51.6	51.3	52.9	52.3	741	738	745	745	737	741
Swede	37.5	36.3	40.3	40.6	42.1	39.4	816	820	800	801	794	806
F. rape[†]	51.2	59.3	67.6	73.5	70.6	64.4	753	713	669	638	653	685
Mean	47.0	49.6	53.2	55.1	55.2		770	757	738	728	728	
LSD[‡] (0.05), PD	5.6						30					
LSD (0.05), Sp	12.3						54					
LSD (0.05), PDxSp	NS						NS					

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

§ Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

Table 3.48. Mean forage quality (NDFD and TDN) of forage brassica root/stem in three species and five plant densities (PD) combined across four environments in Fargo and Prosper ND, in 2012 and 2014.

	NDFD						TDN					
Species	PD1[§]	PD2	PD3	PD4	PD5	Mean	PD1	PD2	PD3	PD4	PD5	Mean
	g kg^{-1}											
Kale	747	742	749	749	741	745	725	723	736	735	729	730
Swede	827	832	811	814	806	818	773	780	768	770	767	772
F. rape[†]	752	712	673	647	660	689	719	699	666	651	660	679
Mean	775	762	744	737	736		739	734	723	719	719	
LSD[‡] (0.05), PD	27						NS					
LSD (0.05), Sp	56						21					
LSD (0.05), PDxSp	NS						NS					

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[§] Targeted PD1 = 33 plants m^{-2}; PD2 = 44 plants m^{-2}; PD3 = 66 plants m^{-2}; PD4 = 133 plants m^{-2}; PD5 = 200 plants m^{-2}.

3.4.5. Forage brassica N and S effect

The analysis of variance combined across three environments for Prosper in 2012 and 2014 and Walcott 2014, for relative values (RV) of leaf, root/stem, total forage biomass yield (leaf + root/stem), dead matter yield, total biomass yield, and total N are presented in Table 3.49. The triple interaction of speciesby N by S is a false interaction due to magnitude differences among species. The double interactions N by S and S by species were not significant for any parameter, and N by species was significant only for dead matter due to the effect of the magnitude. The S main effect was not significant. Species main effect was significant for all parameters except leaf yield, total leaf N and total root/stem N. The N main effect was significant for all parameters evaluated.

The same ANOVA is presented in Table 3.50, but with the absolute values. Although in general, significances were similar but there were a few differences compared with the relative values. The N main effect for absolute values was significant for all parameters evaluated. The species main effect was only significant for root/stem yield, leaf + root/stem yield, total biomass yield and total leaf + root/stem N. The S main effect was not significant for any parameter evaluated. Forage brassicas often respond strongly to N but seldom to S (Wilson et al., 2006; Fletcher et al., 2010a). Table 3.51 and 3.52 are ANOVA for leaf and root/stem forage quality. All the parameters evaluated were not significant for the main effects species, N, and S.

Table 3.49. Analysis of variance and mean squares of relative values for brassica leaf, root/stem, leaf + root/stem, dead matter and total biomass yield, and total N for leaf, root/stem and total forage yield for N and S rates in Prosper 2012 and 2014 and Walcott, ND, in 2014.

Source of variation	df	Leaf yield§	Root/ stem yield	Leaf and root/stem yield	Dead matter	Total biomass yield	Total leaf N	Total root/ stem N	Total forage N ¶
Env†	2	245	5468	6367	1885	6670	2319	3070	4489
Rep(Env)	6	606	233	361	667*	330	214	454	359
Sp	1	396	53389*	33866**	13005*	29466**	8282	29773	25968*
Env x Sp	2	7450*‡	1194	204	150	216	709	2175	1363
Env x Spx Rep	6	707***	139	226	117	133	612**	189	407*
N	4	3903***	1348*	2670**	2049**	2428**	4543**	2292**	3437***
Env x N	8	263	228	318	218	217	325	179	118
S	1	1786	480	1061	85	957	123	281	218
Env x S	2	1376	853	1181	182	772	552	777	832
N x S	4	230	361	317	197	192	240	262	222
Env x N x S	8	269	247	277*	376	240*	257	202*	191*
N x Sp	4	106	86	72	464*	125	75	141	141
Env x N x Sp	8	461	187	270*	111	195	238	221*	236*
S x Sp	1	0.006	161	87	218	166	64	367	358
Env x S x Sp	2	13.2	470*	261	163	176	49	486**	203
N x S x Sp	4	255	404*	422*	81	292*	231	322**	286*
Env x N x S x Sp	8	149	83	74	231	66	188	45	56
Error	108	149	141	143	145	113	154	155	140
CV, %		25	31	26	20	21	30	34	28

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Mean squares values in columns 1-5 were divided by 1000, but not in columns 6-8.

¶Total N = leaf + root/stem N.

Table 3.50. Analysis of variance and mean squares of absolute values for brassica leaf, root/stem, leaf + root/stem, dead matter and total biomass yield, and total N for leaf, root/stem and total forage yield for N and S rates in Prosper 2012 and 2014 and Walcott, ND, in 2014.

Source of variation	df	Leaf yield[§]	Root/ stem yield	Leaf and root/stem yield	Dead matter	Total biomass yield	Totael leaf N	Total root/ stem N	Total forage N[¶]
Env[†]	2	19577	199414	281525	190096***	922590	79425	34552	196746
Rep(env)	6	2565	3302	10839	2091*	13854	644	1925	4158
Sp	1	4068	851286**	973068**	30190	1346052**	19251	119129	234224*
Env x Sp	2	26761*[‡]	8532	5154	1986	5649	3179	7908	7781
Env x Sp x rep	6	3318***	1904	6393	372	6171	2417***	734	5083**
N	4	15018***	21268*	70275**	4021**	107042**	6887***	9653**	32268***
Env x N	8	632	3877	6544	316	8843	132	879	1196
S	1	6645	4115	21223	633	29195	18	755	540
Env x S	2	6063***	14617	36627	376	33761	1357	3502	9168
N x S	4	953	5299	8683	224	7055	472	1046	1909
Env x N x S	8	1223	3899	9205*	393	10674*	431	799*	1908*
N x Sp	4	377	1321	1871	1099	5287	273	591	1410
Env x N x Sp	8	1692*	3227	7208	405	8818*	484	998**	2427*
S x Sp	1	0.1	1073	1096	1006	4205	214	1164	2378
Env x S x Sp	2	51	8958*	7829	454	8387	97	2128**	1809
N x S x Sp	4	1015	6310*	11837*	209	11641*	302	1248**	2432*
Env x N x S x Sp	8	647	1221	2180	584	2392	217	142	413
Error	108	637	2571	4463	374	5572	333	690	1470
CV %		25	31	26	20	21	30	34	28

[†] Env=Environment, Rep=Replicate, Sp= Species and cultivars.
[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean squares values in columns 1-5 were divided by 1000, but not in columns 6-8.
¶Total N accumulation = N accummulated by leaves + root/stem.

Table 3.51. Analysis of variance and mean squares of forage quality components of brassica leaves for N and S rates in Prosper 2012 and 2014, and in Walcott, ND, in 2014.

Source of variation	df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	2	60970	109225	75505	17385	2481	24339	34015	67638***
Rep(Env)	6	1063	1889	327	51	86	158	82	858*
Sp	1	8989	41466	1875	3389	769	16859	7432	18269
Env x Sp	2	5440	73904***	26503*	12434**	5254***	3837	1681	5848
Env x Sp x Rep	6	1377***[‡]	1371***	454	273*	99***	214*	125	1408***
N	4	1518	1914	780	467	97	194	55	1333
Env x N	8	416	1056	551	397	65	348	195*	457
S	1	736	6504	1543	524	370	236	13	495
Env x S	2	846	2370	809	117	89	368	222	1009*
N x S	4	27	81	127	88	2	39	30	22
Env x N x S	8	325	481	461	174	31	67	90	513
N x Sp	4	286	231	1163	659	33	41	52	114
Env x N x Sp	8	583	431	458	311*	35	259	236*	433
S x Sp	1	358	2054*	148	0.005	97*	598	182	428
Env x S x Sp	2	854	67	98	329	5	482	149	1088*
N x S x Sp	4	733	237	166	72	8	164	134	925
Env x N x S x Sp	8	263	217	389	186	21	124	105	396
Error	108	280	301	225	123	20	93	89	318
CV, %		11	14	6	6	9	1	1	2

[†] Env=Environment, Rep=Replicate, Sp= Species and cultivars.

[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 3.52. Analysis of variance and mean squares of forage quality components of brassica root/stem for N and S fertility in Prosper 2012 and 2014, and in Walcott, ND, in 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	2013	13055	467585	269692	15525	411292	275838	96691
Rep(Env)	6	278	815	1029	632	53	1063	1034	736
Sp	1	18666	39073	733317	438376	30135	661025	714067	377346
Env x Sp	2	3408	5476	45904**	29045**	2257**	50573**	42278*	24718***
Env x Sp x Rep	6	239***‡	651	1262*	722*	44	1134	1244*	688**
N	4	316	1045	1432	910	80	1936	1631	785
Env x N	8	159	526	784	519	47	1215	838	454
S	1	765	3125	186	216	37	777	61	1307
Env x S	2	584	2256	224	207	37	716	197	450
N x S	4	56	208	2417**	1463**	102*	2549**	2421**	629*
Env x N x S	8	68	246	234	132	16	284	226	149
N x Sp	4	124*	283	1496	844	50	1126	1171	386
Env x N x Sp	8	25	131	1031*	664**	68**	1576**	1401***	593*
S x Sp	1	948	3538	159	144	35	423	18	1271*
Env x S x Sp	2	322*	1159*	1960**	1105**	80**	2085**	2954***	50
N x S x Sp	4	29	94	436	259	29*	543	407	227
Env x N x S x Sp	8	57	166	183	100	7	148	112	132
Error	108	49	165	458	275	24	540	453	179
CV, %		9	12	6	6	10	3	3	2

† Env=Environment, Rep=Replicate, Sp= Species and cultivars.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

The relative values for leaf and root/stem yield, total forage biomass yield (leaf + root/stem), dead matter yield, total biomass yield (leaf + root/stem + dead matter biomass yield) and total N showed linear response with increasing N rates (0, 50, 100, 150, and 200 kg N ha^{-1}) (Figs. 2, 3, and 4). These increments in yield with increased N rates are in accord with Chakwizira et al. (2015), who reported a linear response to N rates up to 200 kg N ha^{-1}. Other authors also reported increments in yield with increasing N rates (Jung et al., 1984; Albayrak and Camas, 2005), however, these authors find quadratic response instead of the linear response observed in the present study. In most of the cases, the difference in biomass yield between the highest N rate (200 kg N ha^{-1}) and the lowest (0 kg N ha^{-1}) was between 15% (dead matter yield) and 23% (leaf yield). The differences in total N was higher in leaves with 33% and lowest in root/stem with 20%, when the highest and lowest N rates per each parameters were compared. Even though S main effect was not significant for biomass yield for this experiment (Table 3.50), the differences between 0 S and 40 kg S ha^{-1} were between 1 and 6 %, with the highest difference in leaves and lowest in dead matter (data not shown).

The trend observed in N as main effect could be explained because brassica forages respond to N fertilization up to 400 kg N ha^{-1} (Fletcher et al., 2010a; Chakwizira et al., 2015). The available N for forage brassicas (swede and kale) in the present experiment could have limited the growth to reach the maximum potential yield, thus brassicas showed a lineal response instead of typical quadratic response observed in experiments with different N rates (Albayrak and Camas, 2006). Another important factor that could explain the observed response to N fertilization is the N soil content. Prosper 2012 and Walcott 2014 shown 44 and 31 kg N ha^{-1} (N-NO_3 in the soil at 0-60 cm). The soil N-NO_3 plus the highest N rate used in the present experiment would have had less than 250 kg N ha^{-1} available for brassica growth, in these two environments (Table 3.3), which is less than the recommendations of Chakwizira et al. (2015). Conversely, Wilson and Manley (2006) did not find a response to N in kale because the N content of the soil was high. According to Fletcher et al. (2007), kale can have null response to N in soils with high NO_3-N; conversely, in low N soils the response is usually significant. However, is important to know that forage brassicas can take up water and nutrients from 0.9 to 1 m deep (Fletcher et al., 2010a; Fletcher and Chakwizira, 2012). Thus, the N available for plant growth could have been greater than 250 kg N ha^{-1}. Additionally, Vos and van der Putten (1997) reported that the response to N fertilizer in brassicas depends on the amount of residual and mineralized N in the soil, which is influenced by the previous cropping history.

Nitrogen response also is related with the water availability. The response can be greater when irrigation is used or at least adequate rainfall occurs during the growing season (Fletcher et al., 2010b; Chakwizira et al., 2013; Chakwizira et al., 2015). Brassicas must have at least 500 mm of water to avoid yield reduction by water deficit (Wilson and Maley, 2006). Fletcher et al. (2010b) mentioned that drought conditions of 100 mm rainfall produce half of yield compared with full irrigation (328 mm). However, in the environments evaluated in the present experiments the rainfall was low (210, 267, and 251 mm of rainfall in Prosper 2012 and 2014 and Walcott 2014, respectively). This agrees with de Ruiter et al. (2009), who reported water availability is the main environmental source of forage yield variation in brassicas.

Also, an interesting aspect is related with the trend shown by relative leaf and dead matter biomass yield. With 0 kg N ha^{-1}, forage yield was composed of 31% leaves and 58% dead matter, but with the highest N rate applied, the percentage of both leaves and dead matter increased (Figs. 2 and 3), respectively. That probably occurred, because with limited N the leaf area declined faster as leaves senesced mobilizing N to growing points and new leaves (Wilson and Maley, 2006). The relative total N was higher for leaves than for root/stem, and as N rates increased total N increased. The total N rate was greater for leaves which can be observed in Fig. 2. These results are in accord with the information provided by Chakwizira et al. (2015), and Wilson and Maley (2006).

It was interesting that forage quality was not affected by N rates as expected, especially for CP. Several studies have reported that CP can increase in leaves and root/stem with N fertilization but the response depends on N fertilization and weather conditions (Pelletier et al., 1976; Albayrak and Camas, 2005). In general, higher CP is explained by higher leaf:stem ratio which is promoted by N availability (Pelletier et al., 1976; Moate et al., 1999). Conversely, other authors did not find effect of increasing N rates on leaf and root yield of turnip (Keogh et al, 2011). The lack of response to N was likely due to high soil N or high mineralization rate of residues of the previous crop.

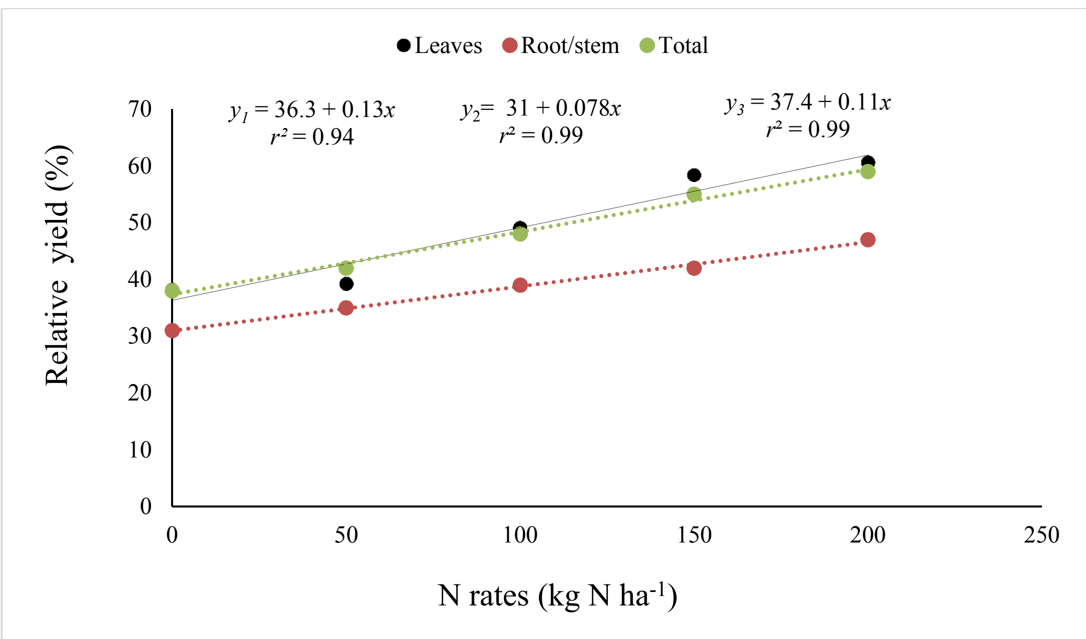

Fig. 3.2. Regression model for relative leaf (y_1), root/stem (y_2), and total forage yield (leaf + root/stem, y_3) of swede and kale averaged affected by different N rates averaged across three environments in Prosper and Walcott, ND, in 2012 and 2014.

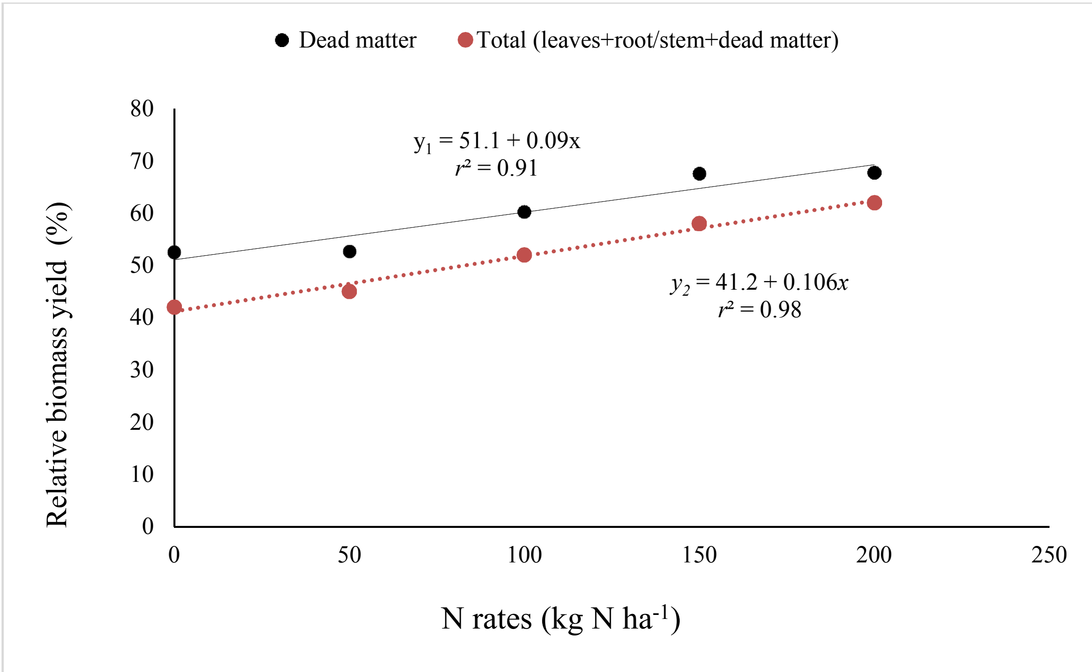

Fig. 3.3. Regression model for relative dead matter (y_1) and total biomass yield (leaf + root/stem + dead matter, y_2) of swede and kale averaged, affected by different N rates averaged across three environments in Prosper and Walcott, ND, in 2012 and 2014.

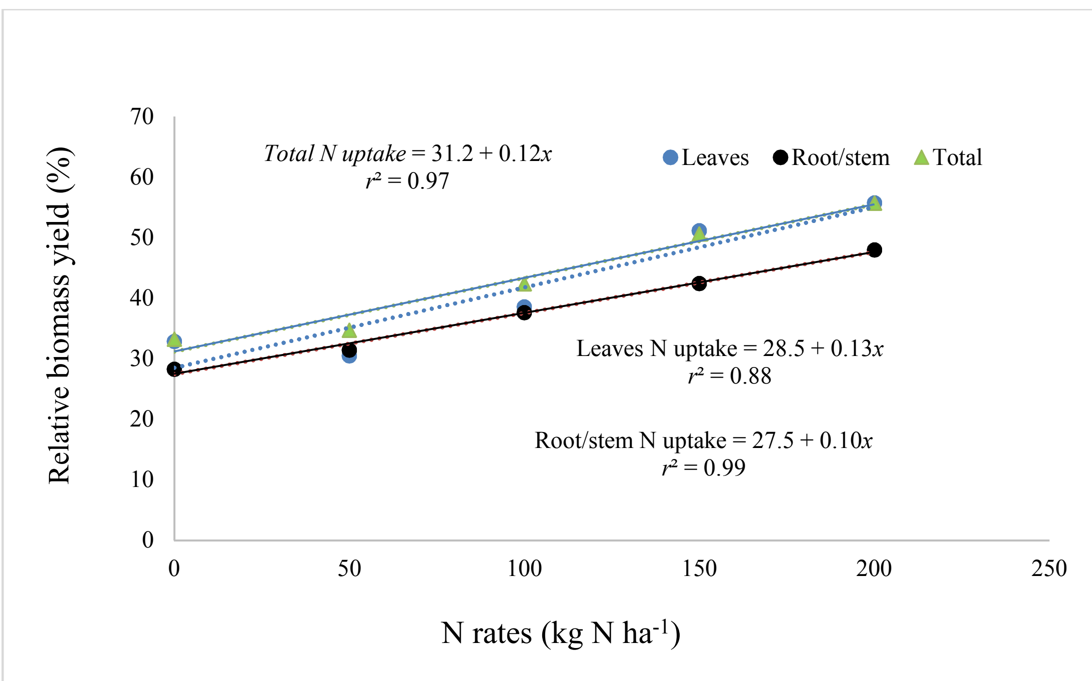

Fig. 3.4. Regression model for relative leaf, root/stem, and leaf + root/stem total N of swede and kale averaged, affected by different N rates averaged across three environments in Prosper and Walcott, ND, in 2012 and 2014.

3.5. Conclusions

Full season forage brassicas have an interesting potential in North Dakota, due to the high biomass yield and forage quality. However, differences among species and cultivars within a same species were observed. Forage quality of all brassicas was high, with highly digestible forage. Brassica leaves have high crude protein, and stems/roots have high energy, hence they are a very good source for milk and beef production, respectively. In general, species with thick stems had higher fiber content and lower fiber digestibility than species with emlarged roots, and vice versa, but the fiber in leaves are similar.

Kale and swede had the highest forage yield, mainly because they have a longer growth period to accumulate biomass. Some forage rape cultivars and hybrids also produce high forage biomass, and they have the ability to regrowth, which is desirable characteristic for grazing utilization during a long period. Conversely, species with longer growth period have not time for regrowth, thus, they must be utilized completely in just one grazing.

Sowing date can affect yield components, but in general did not influence forage quality of brassicas. Delaying sowing date reduced total forage yield in all species, but kale and swede are more affecte due to the longer growth period that they need to reach maturity. Root/stem yield is more affected than leaf yield when the sowing date is delayed. Hence, beef producers that need high energy for winter feeding, must sow kale or swede early in spring to maximize the forage yield.

Plant density did not have an effect on forage yield averaged across environments and species, probably because forage brassicas have the ability to self-thinning, adjusting the plant density to minimize the competition. However, a significant interaction was observed in swede, with higher root yield compared with other species, mainly at lower plant density

Plant density has an effect on forage quality, because higher plant densities increase fiber content (NDF) and decrease the digestibility of the of the fiber (NDFD). Hence, farmers that need highly digestible forage for livestock, must reduce plant density to increase forage brassica digestion.

Kale and swede forage biomass yield (leafand root/stem) increased up to 200 kg N ha^{-1} in a linear response, indicating that these species could actually have a response to greater N rates. Sulfur and the interaction between N and S did not have an effect in forage yield and quality. Fields with higher N or low water availability can not show positive response to N fertilization. Brassicas under irrigation or grown in zones with high rainfall during spring and summer, can response to higher N fertilization, producing higher biomass yield.

3.6. Literature cited

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CHAPTER 4. AGRONOMIC STUDIES OF BRASSICA COVER CROPS

4.1. Abstract

Cover crops are defined as a crop to provide soil protection, but they offer a variety of ecosystem services and can be used as forages. The objectives of this study were: 1) to determine the brassica cover crops that adapt to North Dakota and can produce high forage yield of good quality, and 2) to determine the sowing date and plant density to optimize forage yield.

Several species of forage brassicas were sown after August in two locations, in North Dakota in 2013-2014. In general, biomass yield was higher for tops than roots in all species. Turnip cv. Appin had the highest above ground biomass yield of all species evaluated while root yield and total N was highest in radish cv. Groundhog. Forage quality varied among species and part of the plant (roots and tops). Tops had higher CP than roots. Radish tops had the highest CP, NDF, and ADF while turnip roots had the highest CP. Despite the differences, all forage brassicas had very high digestibility and are of high quality forage for grazing late in the fall in North Dakota. The first sowing date (8-9 August) had higher or similar forage yield than the second sowing date, indicating that forage brassicas for grazing should be sown as soon as possible after wheat harvest in North Dakota to optimize forage yield and quality. Forage quality was not influenced by sowing date. The highest plant density evaluated (≥200 plants m^{-2}) produced the highest forage yield across all species, although fiber components (NDF and ADF) were higher, reducing the forage quality. All forage brassicas can be used as cover crops for grazing in North Dakota, but it is important to know that marked differences exist among species and cultivars within species. Before deciding which forage brassica(s) to select, growers should consider cultivar trials near their location to identify the species and cultivars with the highest potential forage yield and quality.

4.2. Introduction

Cover crops are defined as a crop to provide soil protection, and to enhance soil characteristics between two cash crop cycles or between trees in orchards or vineyards (SSSA, 2008), providing several environmental and agronomic benefits (Weil and Kremen, 2007). Cover crops have been used since the Roman Empire in Europe, and from middle 1800's in the USA, until they were shelved when synthetic fertilizer become popular in 1950's (White, 2014). Nowadays, they have resurged covering 10.3 million ha in USA in 2013, with a goal of 20 million ha by 2020 (White, 2014). North Dakota had an estimated area of 86,000 ha of brassica cover crops in 2012 (Berti et al., 2015).

Annual species and/or their mixtures can be used as cover crops due to their faster growth in poor conditions (Fageria et al., 2005). Plants belonging to *Fabaceae* (legumes), *Poaceaea* (grasses) and *Brassicaceae* (brassicas and mustards) are the most widely used as cover crops (Clark et al., 2007; Chen et al., 2007; Cupina et al., 2011; Gieske et al., 2016). Cover crops provide several environmental and agronomic benefits (Weil and Kremen, 2007) among them: 1) enhancing soil fertility with essential mineral nutrients, 2) reducing nutrient losses (Meisinger et al., 1991; Sainju et al., 1998; Vos and Van Der Putten, 2004; Fageria et al., 2005; Cupina et al 2011; Dagel et al., 2014), 3) increasing soil organic matter content and C sequestration (Sainju et al., 2001; Dabney et al., 2001; Fageria et al., 2005), 4) improving soil structure, conserve soil moisture, decrease compaction, and reduce soil erosion (Williams and Weil, 2004; Fageria et al., 2005), 5) increasing soil biological activity (Fageria et al., 2005), 6) suppressing weeds, decreasing disease and insect problems (Fisk et al., 2001; Fageria et al., 2005), and 7) improving yield of subsequent crops (Sainju et al., 2001; Fageria et al., 2005; Dagel et al., 2014). In spite of these benefits, the integration of cover crops in cropping systems brings costs and disadvantages.

The direct costs are associated with sowing (Snapp et al., 2005), while perceived disadvantages include competition for water with the main crop, immobilization of N (Dabney et al., 2001), and delaying the soil warming in the spring delaying sowing (Vos and Sumarni, 1997; Snapp et al., 2005; Stavi et al, 2012).

Brassica cover crops can improve several soil physical traits. The plant biomass (tops and roots) of forage radish can increase soil organic carbon content (Mutegi et al., 2011; Stavi et al., 2012). These organic components improve soil structure and increase soil biological activity (Carrera et al., 2007). Soil aggregation and porosity is increased by brassica cover crops, enhancing water-holding capacity (Prichard, 1998, Dabney et al., 2001) and air and water conductivity (Chen et al, 2014). Water conservation is also improved by the residue left by cover crops on the top soil (Clark et al., 2007). Soil bulk density can be enhanced with brassica cover crops (Stavi et al., 2012) and soil compaction is reduced (Williams and Weil, 2004; Clark et al., 2007). The long and thick taproot can break soil compaction efficiently (Weil and Kremer, 2007; Chen and Weil, 2010; Chen and Weil, 2011). Once the taproots are killed and decomposed, root channels left in the soil can facilitate root growth of the next cash crop improving water infiltration (Weil and Kremer, 2007; Chen et al, 2014). Soils that have had forage radish have reduced water run-off when high rainfall events occur (Weil and Kremer, 2007). Brassica cover crops can prevent soil erosion caused by winter and spring rains (Dabney et al., 2001; Weil and Kremer, 2007), reducing the forces of soil detachment and transport (Kaspar and Singer, 2011).

Brassica cover crops improve soil fertility by capturing leachable nutrients (Dabney et al., 2001; Sarrantonio, 2007). Brassicas are the most efficient crops in reducing NO_3-N leaching and they can decrease leaching by 60 to 90% (Kristensen and Thorup-Kristensen, 2004; MacDonald et al., 2005; Dean and Weil, 2009; Liu et al., 2015; Lacey and Armstrong, 2015). The root morphology and its ability to grow fast and deep in the soil are the main contributors to its efficient scavenging ability (Sainju et al., 1998; Chen et al., 2007; Weil and Kremen, 2007). The amount of N accumulation in the tissue is affected by species/cultivar, environment, and management (Thorup-Kristensen, 1994; Brennan and Boyd, 2012; Lacey and Armstrong, 2015; Gesike et al., 2016). Brassica cover crops can increase solubilization and availability of P in the soil (Shahbaz et al., 2006; Marschner et al., 2007; Makela et al., 2011). However, several freezing/thawing cycles can release the P content in the tissue, increasing potential water soluble P release to the environment (Riddle and Bergström, 2013; Liu et al., 2014; Liu et al., 2015).

Brassica cover crops are used widely in pest control. Isothiocyanates and other toxic compounds are generated from the hydrolysis of glucosinolates (Brown and Morra, 1996; Haramoto and Gallandt, 2005; Laegdsmand et al., 2007). These toxic secondary compounds have the potential to control weeds, disease, insects, and nematodes (Brown and Morra, 1997; Rosa et al., 1997; Sarwar et al., 1998; Kirkegaard and Sarwar, 1998; Gardiner, 1999; Haramoto and Gallandt, 2004; Malik et al., 2008; Weil and Kremer, 2007; Kirkegaard et al., 2008; Ackroyd and Ngouajio, 2011; Makela et al., 2011; Björkman et al, 2015).

The interaction between species/cultivar, location, season/climate, and management will determine the cover crops biomass production (Balkcom et al., 2007). Brassica species can produce between 3.0 and 10 Mg DM ha^{-1} (Balkcom et al., 2007; Björkman et al., 2015); radish biomass yield ranges from 1.2 to 13.1 Mg DM ha^{-1} (Ngouajio and Mutch, 2004; Balkcom et al., 2007; Samarappuli, and Berti, 2011; Geiske et al., 2016) and rapeseed ranges between 2.2 to 6.7 Mg DM ha^{-1} (Balkcom et al., 2007; Chen et al., 2007). In general, early fall sowing dates improves biomass yield (Balkcom et al., 2007; Weil et al., 2009), delaying the sowing date reduces growth and yield (Villalobos and Brummer, 2013). Brassica cover crop sowing rates range between 5.6 to 14.6 kg ha^{-1} but is increased by 25 to 50% when broadcasted (Balkcom et al., 2007).

The specific objectives of this research were: 1) to identify brassicas species and cultivars with high biomass yield and quality when grown as cover crops in North Dakota; and 2) to determine the optimum sowing date and plant density of different brassica cover crop species.

4.3. Materials and methods

4.3.1. Experimental sites

Field experiments were conducted from 2013 to 2014 located at two North Dakota State University (NDSU) research sites at Prosper (46°58´N, 97°3´W, elevation 284 m), and Fargo (46°52´N, 96°47´W, elevation 274 m). The soil type at Prosper is a Kindred-Bearden silty clay loam (Kindred: fine-silty, mixed, superactive, frigid Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll; Perella: fine-silty, mixed, superactive, frigid Typic Endoaquoll). The soil type at Fargo is; Fargo silty clay soil (fine, smectitic, frigid Typic Epiaquert) (Web Soil Survey, 2013). The previous crop at all two locations was either oat (*Avena sativa* L.), spring wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) and the experimental plots were planted using a no-till system into the previous year crop residue.

4.3.2. Experimental design and management

Three experiments were conducted with different brassica species as cover crops: 1) species/cultivars experiment (S/CE), 2) sowing date experiment (SDE), and 3) sowing rate/density experiment (SR/DE). The S/C experiment were conducted at Fargo and Prosper in 2013 and 2014. Five different species: turnip (6 cultivars), forage rape (2 cultivars), hybrids (5 cultivars), radish (3 cultivars), and Ethiopian cabbage (1 cultivar) were evaluated (Table 4.1).

All experiments were designed as a randomized complete block design (RCBD), with three replicates.

Table 4.1. Species/cultivars, 1000-seed weight and sowing rate of cover crops planted at Fargo and Prosper, ND, in 2013 and 2014.

Specie/Cultivar	Company	1000-seed weight	Sowing rate†	
			2013	2014
		g	-------kg ha^{-1}------	
Turnip				
Appin	Welter Seed & Honey	4.4	5.7	5.8
New York	MillBorn Seed	1.8	5.9	5.8
Rack	Ampac	2.8	5.6	5.6
Pointer	Ampac	2.6	5.6	5.7
Purple Top	Millborn Seeds	2.4	5.6	5.6
Barkant	Barenburg	1.9	5.6	5.9
Rape				
Barnapoli	Welter Seed & Honey	3.5	6.8	6.8
Dwarf Essex	Millborn Seeds	4.7	7.1	7.2
Hybrid‡				
Winfred	Millborn Seeds	4.7	6.9	6.8
Pasja	Ampac	2.5	7.1	7.3
Hunter	Millborn Seeds	3.1	6.7	6.8
T-Raptor	Barenburg	3.2	6.7	7.0
Vivant	Mountain View Seeds	2.8	6.7	6.7
Radish				
Daikon	Millborn Seeds	14.9	11.2	11.3
Graza	PGG	-	12.0	12.3
Groundhog	Welter Seed & Honey	18.5	11.4	11.8
Ethiopian cabbage				
Corinne	PGG	2.8	7.1	7.0

† The sowing rates were corrected for % seed germination. Germination tests were conducted per every species/cultivars, every season.
‡ Hybrid Winfred (*Brassica rapa* L. x *B. oleracea* L.), hybrid Pasja, Hunter, T-Raptor, and Vivant (*Brassica rapa* L. x *B. napus* L.)

The SD experiment was conducted at Fargo in 2014 and Prosper in 2013 and 2014. The experimental design was a RCBD with three replicates, and a split-plot arrangement. The sowing dates (two) were the main plot. The sub-plots were four species, turnip cv. Purple Top, forage rape cv. Dwarf Essex, radish cv. Daikon, and Hybrid cv. Pasja. The SR/D experiment were conducted in Fargo in 2014 and Prosper in 2013 and 2014. The experimental design was a RCBD with three replicates, and a split-plot arrangement. The four plant densities were assigned to the main plot. The brassica cover crops turnip cv. Purple Top, radish cv. Daikon, and hybrid cv. Pasja were assigned to the sub-plot.

Experiments were established in a no-till system, on top of cereal stubble (oat, wheat, or barley), using a plot-cone planter (Wintersteiger, Plotseed XL, Salt Lake City, UT). Glyphosate [n-(phosphonemethyl)glycine] was applied before or after sowing to control weeds or cereal volunteer regrowth, with an application rate of 1.1 kg ai ha^{-1}. Cover crops were sown using a specific sowing rate of pure live seed (PLS) according with the recommendation for each species (Table 4.1) and a depth of approximately 8 to 15 mm. The SR/D plots were sown with the normal sowing rate for each species. One plot was left unthinned and the others were thin down to 15, 10, and 5-cm apart in the row to obtain four different densities (44, 66, 133, and >200 plants m^{-2}). Each plot was 1.2 m wide and 6.1 m long (7.4 m^{-2}), with 8 rows of crop 15 cm apart. The sowing date for S/C and SR/D experiments was between August 8 to 12 in 2013 and 2014 (Table 4.2). The SD experiment had two SD, August 9 to 12 for the first SD, and August 23 to 25 for the second SD, considering both years (Table 4.2).

One application of Sniper (bifenthrin: (2 methyl[1,1'-biphenyl]-3-yl) methyl 3-(2-chloro-3,3,3-trifluoro- 1-propenyl)-2,2-dimethyl-cyclopropanecarboxylate) to control flea beettle (*Phyllotetra cruciferae* L.) was done two weeks after sowing. Helix Xtra (difenoconazole: 1-[2-[2-chloro-4-(4-chlorophenoxy)phenyl]-4-methyl-1,3-dioxolan-2-ylmethyl]-1H-1,2,4-triazole) was used as a seed treatment to prevent flea beetle damage using 1.5 L 100 kg $seed^{-1}$, with no apparent benefits in the control. Fertilizers were not applied to cover crop experiments.

Table 4.2. Sowing and harvest dates and number of days from sowing to harvest in each experiment at Fargo and Prosper, ND, in 2013 and 2014.

	2013			2014		
Exp./Location	Sowing	Harvest	No. days	Sowing	Harvest	No. days
Fargo						
S/CE†	8 Aug	21 Nov	105	11 Aug	30 Oct	80
SR/DE‡				11 Aug	4 Nov	85
SDE¶						
Date 1				11 Aug	29 Oct	79
Date 2				26 Aug	29 Oct	64
Prosper						
S/CE	9 Aug	15 Nov	99	12 Aug	31 Oct	80
SR/DE	9 Aug	19 Nov	103	12 Aug	3 Nov	83
SDE						
Date 1	9 Aug	12 Nov	96	12 Aug	24 Oct	74
Date 2	23 Aug	12 Nov	82	25 Aug	24 Oct	61

†S/CE: Species/cultivar experiment
‡SR/DE: Sowing rate/density experiment
¶ SDE: Sowing date experiment

4.3.3. Evaluations

Brassica cover crops were harvested in November in 2013 and in October and early November in 2014 (Table 4.2). Three plant height measurements were taken before harvest in each plot from the soil surface to the longest vegetative part of the plant. Biomass yield was measured harvesting 1m^2 randomly in each plot to determine both above and belowground biomass. Enlarged roots and/or taproots were removed from the soil pull them up or using a shovel, to harvest the maximum of enlarged or taproot tissue. Each whole plant harvested was divided in above ground biomass (stems and leaves, henceforth “tops”) and below ground biomass (roots) and bagged separately. Large roots of radish or turnip were chopped in a food processor to 5 mm of thickness or less (Sunbeam food processor Model Le Chef, Chicago, IL) when fresh, leaving thin slices of 5 mm. All the samples bags were weighed wet and dried at around 43.3°C. Samples remained in the driers several days until the weight loss was stabilized and were weighed to obtain the dry weight.

Dried samples were ground in a mill (Wiley Mill standard Model Nº3, Philadelphia, PA) to 1-mm mesh and then sent to laboratories to determine nutritional values. All the samples were analyzed in a near infrared reflectance spectroscopy (NIRS) (Foss-Sweden Model 6500, Minneapolis, MN) in Dr. Undersander's laboratory, Agronomy Department, University of Wisconsin, Madison, following the methods described by Abrams et al. (1987). Chemical analysis for some samples of leaves, stems, and roots were conducted at Animal Sciences Nutrition Laboratory at NDSU. The results were used to build the equation to determine nutritional values in the NIRS. The component determined were ash, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), neutral detergent fiber digestibility (NDFD), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), and total digestible nutrients (TDN).

The total N in each species/treatment plot was determined from CP content, obtained from NIRS results. Total N was calculated with the equation: N = CP/6.25 (Kjeldahl method) (Speirs and Mitchell, 2013). Total N was calculated arithmetically multiplying the above and below ground forage biomass yield in kg ha^{-1} by the N content. Total N (kg N ha^{-1}) of forage produced was calculated using the N concentration (%) in the tissue (tops or roots), times the total biomass yield produced per ha.

4.3.4. Statistical analysis

The statistical analysis was conducted using standard procedures for a simple RCBD and a RCBD with a split-plot arrangement. Each location-year combination was defined as an 'environment' and was considered a random effect in the statistical analysis. Specie/cultivars, sowing rates, and plant densities were considered fixed effects. Analysis of variance and mean comparisons were conducted using the procedure Mixed of SAS (SAS, 2014). Error mean squares were compared for homogeneity among environments according to the folded *F*-test and if homogeneous, then a combined ANOVA was performed across environments. Treatment means separation was determined by *F*-protected LSD comparisons at the $P \leq 0.05$ probability level.

4.4. Results and discussion

<u>*4.4.1. Rainfall and temperature*</u>

The historical 25-years rainfall average was 467 and 445 mm for Fargo and Prosper, respectively (Fig. 4.1) (NDAWN, 2016). The rainfall was below the 25-year historical average during sowing time (August 2013) in Fargo and Prosper, and in 2014 in Fargo but not in Prosper. Limited rainfall in August 2013 delayed germination and emergence of cover crops. Sowing dates in Fargo and Prosper were 8 and 9 August, respectively, but the first effective rain was in August 29 in Fargo (21 days later) and 25 August in Prosper (16 days later). During September and October 2013, the rainfall was above the 25-year average in Fargo and Prosper, but in 2014 rainfall was below average in both places. October 2014 was the driest month of the season in Fargo and Prosper with less than 10 mm of rainfall, which likely affected the cover crops growth late in the season. Water availability is the most important factor on forage brassica growth (de Ruiter et al., 2009; Fletcher et al., 2010). Total rainfall for the whole growing season (August to October) was between 220 and 224 mm in Fargo and Prosper 2013, respectively, and between 93 and 110 mm for Fargo and Prosper 2014, respectively.

The minimum and maximum temperature recorded during 2013 and 2014 were relatively similar with the 25-year minimum and maximum temperature averaged across the growing season (Fig. 4.1). In 2013, the minimum and maximum temperature were between 1 and 3°C higher than the 25-year average between August and October in Fargo and Prosper. Differences between minimum and maximum temperature during August to October 2014 were lower compared with 2013. In general, daily temperature decreased from 13 and 28°C in July to 1 and 15°C in October, for minimum and maximum, respectively, slowing down growth at the end of the season. Temperature for germination was optimal during August, because the bare soil in Fargo and Prosper in both season was >21°C at sowing (data not presented). This temperature is optimal for a fast germination and emergence (Smith and Collins, 2003), allowing plants to emerge in 10 days or less after sowing as long soil water is available (Jung et al., 1986).

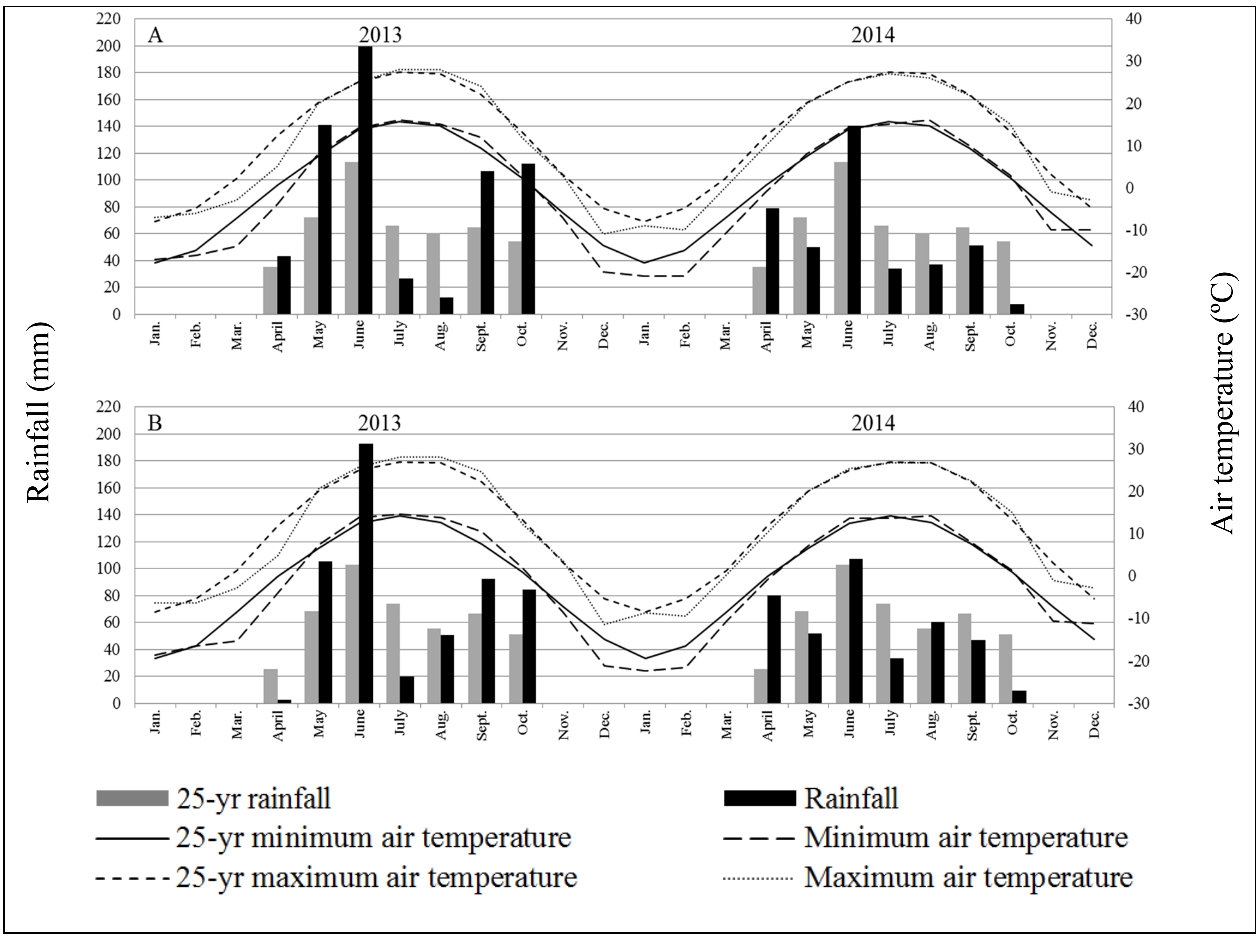

Fig. 4.1. Monthly average minimum and maximum air temperatures and monthly total rainfall in 2013 and 2014 compared with the 25-yr (1990-2014) average at Fargo (A) and Prosper (B).

4.4.2. Brassica cover crops species and cultivars performance

The analysis of variance across three environments in Fargo 2014 and Prosper, ND, in 2013 and 2014, for tops (leaves + stems), roots, total forage yield (tops+roots), total N in tops, roots, and total N of forage yield are presented in Table 4.3. Species and cultivars, henceforth 'species', main effect was significant for tops and roots biomass yield and roots total N. The interaction between species and environment was not significant for any parameters.

Even though cover crops were sown at a time of the season with high temperature (over 20°C), most of the growth occurred when temperaures started declining, which affected their biomass accumulation (Wiedenhoeft, 1993; de Ruiter et al., 2009). Additionally, water supply was low in most of the cases, during sowing and growing, reducing total biomass yield (Rowe and Neilsen, 2010).

Top biomass yield fluctuated between 1.6 Mg ha^{-1} in radish cv. Graza and 3.6 Mg ha^{-1} in turnip cv. Appin (Table 4.4). Turnip cv. Appin had significantly higher tops yield than all radish cultivars, forage rape cv. Dwarf Essex, and turnip cv. Rack and New York. The root biomass yield was lower compared with that of tops and fluctuated between 0.5 and 1.8 Mg ha^{-1}. 'Groundhog' radish had the highest root yield, different than all forage rape and hybrid cultivars, Ethiopian cabbage cv. Corine and radish cv. Graza. The top and root biomass yield in this study were lower than the total biomass yield reported by Dean and Weil (2009), even though their growing season is longer (4 to 5 months). A high leaf/root ratio is normal in cover crops at early stages, because after the initial tap root development, above ground plant parts grow faster (Isse et al., 1999; Dean and Weil, 2009). The total N by tops was not significant, probably due to differences in top biomass yield across environments that masked differences in one particular environment. The total N in roots was the lowest in Ethiopian cabbage cv. Corine and highest in radish cv. Groundhog with 4 and 35 kg N ha^{-1}, respectively. ”Groundhog” was different than most species and cultivars, except turnip cv. Appin and Purple Top, and radish cv. Daikon (Table 4.4). Other authors have reported similar responses in total N by forage radish even in areas with longer growing season, (Isse et al., 1999; Dean and Weil, 2009). However, Kristensen and Thorup-Kristensen (2004) and Weil et al. (2009) reported higher total N than the present study in forage radish due to a rapid growth and high N availability in the soil (Weil et al. 2009), and also, because the radish taproot can reach 1.8 m deep, taking up N from very deep zones (Alayna, 2012). In general, the total N reported in the present study can be considered low, most likely due to lack of water for growth. Nitrogen immobilization could also have played a minor role in the low total N observed since cover crops were sown on cereal residue with a high C:N ratio, (Dean and Weil, 2009).

The analysis of variance across three environments, Fargo 2014 and Prosper 2013 and 2014, indicated the species main effect was significant for all forage quality components of plant tops, except ADL. The interaction between species and environment was significant only for ash, NDF, IVDMD, NDFD and TDN (Table 4.5).

Top ash content fluctuated between 113 g kg^{-1} in Ethiopian cabbage cv. Corine and 196 g kg^{-1} in radish cvs. Daikon and Groundhog (Table 4.6), which were higher or similar in ash content than hybrids, turnips, and forage rape in other studies (Westwood and Mulcock, 2012; Barry, 2013). Differences in ash content reported by other studies is a result of the part of the plant reported, just tops (Westwood and Mulcock, 2012) or the whole plant (Barry, 2013). The species with the highest CP content in the tops was radish, with values of 180 and 178 g kg^{-1} for ‘Groundhog’ and ‘Daikon’, respectively. The lowest CP content was 137 g kg^{-1} in forage rape cv. Hunter and T-Raptor. Radish cv. Daikon had the highest content of NDF and ADF with 268 and 206 g kg^{-1}, respectively. In general, CP was lower than that reported by other researchers (Wiedenhoeft and Barton, 1994; Kaur et al., 2011, Westwood and Mulcock, 2012) which can be explained by low soil water availability and high temperature observed in some environments which likely limited N absorption decreasing the CP content in the tissue (Dean and Weil, 2009). The lowest fiber values were in hybrids cv. Winfred and Hunter with 217 g kg^{-1} of NDF, and 164 g kg^{-1} of ADF with turnip cv. Barkant. Similar fiber content values in hybrids has been reported before (Guilard and Allinson, 1988; Wiedenhoeft and Barton, 1994; Kaur et al., 2011). Environmental conditions such as high temperature, light intensity, photoperiod, and low soil water availability can increase fiber content and decrease CP content (Guillard and Allinson, 1988; Wiedenhoeft and Barton, 1994). Several authors have reported that CP content is about 25 to 60% greater in the aerial part than in the roots (Rao and Horn, 1986; Jung et al., 1986; Smith and Collins, 2003; Nichol et al., 2003; Villalobos and Brummer, 2013; Lemus and White, 2014).

The IVDMD and NDFD values were lower in radish cv. Groundhog with 876 and 920 g kg^{-1}, respectively and highest in hybrid cv. Hunter with 912 and 942 g kg^{-1}, respectively. The lowest TDN was in radish cv. Daikon and Groundhog, with 704 and 705 g kg^{-1}, respectively and the highest value was 800 g kg^{-1} in the hybrid cv. Winfred (Table 4.6). Logically, species with the highest NDF and ADF also had the lowest IVDMD, NDFD, and TDN. Conversely, some hybrids with low fiber content, were the species with higher digestibility. Higher fiber content decreases fiber digestibility and digestible nutrients due to the rumen microbes have more difficulty to digest the fiber (Depeters and Heguy, 2013).

The analysis of variance across three environments, Fargo 2014 and Prosper 2013 and 2014, indicated the species main effect and the species and environment interaction were significant for all forage quality components of roots (Table 4.7). The root ash content fluctuated between 52 and 86 g kg^{-1} and CP between 63 and 126 g kg^{-1}, with the lowest content in Ethiopian cabbage cv. Corine and the highest in turnip cv. Purple Top and Appin, respectively (Table 4.8). The ash content in roots was lower than in leaves because leaves had more contamination with soil because roots were washed before drying them.

Radish was the species with the lowest fiber and lignin content in the roots. The NDF, ADF, and ADL contents were higher in Ethiopian cabbage cv. Corine, with 734, 567, and 133 g kg^{-1}, respectively. Ethiopian cabbage was significantly different with all species and cultivars in all of these three parameters evaluated. The lowest content of NDF, ADF, and ADL was found in radish cv. Daikon, with 216, 167, and 23 g kg^{-1}, respectively. The lower fiber content could be explained by the short growing season. Fiber accumulation accelerates when the plant is reaching maturity (Wiedenhoeft and Barton, 1994), but in this case cover crops grew less than 105 days, remaining in vegetative stage. In addition, radish was the species with the highest IVDMD, NDFD, and TDN with average of 879, 891, and 808 g kg^{-1}, respectively, followed by turnip and hybrids. The lowest IVDMD, NDFD and TDN were found in Ethiopian cabbage cv. Corine, with 357, 370 and 409 g kg^{-1}, respectively, followed by forage rape cv. Barnapoli.

Table 4.3. Analysis of variance and mean squares for tops, roots, top + root biomass yield and total N of brassica cover crops in Fargo 2014 and Prosper 2013 and 2014, ND.

Source of variation	df	Top yield	Top total N	Root yield	Root total N	Top + root yield	Top + root total N
Env[†]	2	6688[‡§]	17312*	5822*	930	10984	15368
Rep(Env)	6	3520**	2887*	625*	282**	6992***	4932**
Sp	16	2307*	176	1418***	726***	2932	1989
Env x Sp	32	1093	913	215	91	1727	1328
Error	96	949	1013	209	78	1661	1430
CV, %		36	47	45	49	35	44

[†] Env=Environment, Rep=Replicate, Sp= Species.

[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

[§] Mean squares values in columns 1-3 were divided by 1000, but not columns 4, 5, and 6.

Table 4.4. Mean biomass yield of tops, roots, total forage, and total N of different species/cultivars of brassica cover crops averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

Species/cultivar	Tops		Root		Total[§]	
	Yield	Total N	Yield	Total N	Yield	Total N
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
Turnip						
Appin	3.6	97	1.4	28	5.0	124
New York	2.4	58	1.2	24	3.6	82
Rack	2.4	61	1.3	21	3.6	82
Pointer	3.3	82	1.3	24	4.6	106
Purple Top	2.7	74	1.3	26	4.0	99
Barkant	3.0	70	1.3	21	4.3	91
Forage rape						
Barnapoli	2.7	68	0.5	5	3.2	74
Dwarf Essex	2.3	56	0.7	9	2.9	65
Hybrids						
Winfred	3.1	73	0.8	9	3.8	83
Pasja	3.2	81	0.6	12	3.8	92
Hunter	3.0	67	0.8	14	3.8	81
T-Raptor	2.8	64	0.6	12	3.5	76
Vivant	2.8	66	0.7	13	3.5	79
Radish						
Daikon	2.1	61	1.5	30	3.6	91
Graza	1.6	47	1.1	22	2.8	69
Groundhog	2.1	61	1.8	35	3.8	95
E. cabbage[†]						
Corinne	2.6	67	0.5	4	3.2	71
LSD[‡] (0.05)	1.0	NS	0.5	9	NS	NS

[†] E. cabbage = Ethiopian cabbage.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.

[§] Total yield includes tops and roots.

Table 4.5. Analysis of variance and mean squares of forage quality components of brassica cover crop tops in three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	Df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	36185***‡	50765***	45528***	23585***	4050***	510*	4545***	43572***
Rep(Env)	6	202	1654**	1072***	182	74*	42	112	334
Sp	16	7851***	1472*	1907***	1249***	59	1040***	345**	9410***
Env x Sp	32	459***	644	497**	148	45	157**	113*	430*
Error	96	192	495	241	125	29	75	69	240
CV, %		8	14	7	6	11	1	1	2

† Env=Environment, Rep=Replicate, Sp= Species.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.6. Mean forage quality components of brassica cover crop tops averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

Species/cultivar	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
	----------------	----------------	----------------	----------------	$g\ kg^{-1}$	----------------	----------------	----------------
Turnip								
Appin	184	157	230	174	47.3	899	936	723
New York	188	147	238	179	47.9	892	926	717
Rack	177	153	233	173	47.2	903	934	731
Pointer	186	144	224	167	48.0	911	940	724
Purple Top	180	156	241	173	46.0	890	928	724
Barkant	178	141	223	164	49.1	907	937	732
Forage rape								
Barnapoli	129	157	226	179	48.3	899	934	782
Dwarf Essex	117	149	234	177	50.7	896	929	795
Hybrids								
Winfred	116	147	217	175	50.1	908	936	800
Pasja	184	148	222	167	48.3	904	936	726
Hunter	174	137	217	167	51.0	912	942	738
T-Raptor	188	137	227	173	51.2	907	934	721
Vivant	187	150	227	170	48.0	910	941	724
Radish								
Daikon	196	178	268	206	43.4	877	925	704
Graza	184	169	244	179	44.3	894	931	719
Groundhog	196	180	263	198	42.1	876	920	705
E. cabbage[†]								
Corine	113	162	227	196	47.1	896	927	795
LSD[‡] (0.05)	21	24	21	12	NS	12	10	20

[†] E. cabbage = Ethiopian cabbage.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.

[§] Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.7. Analysis of variance and mean squares of forage quality components of brassica cover crop roots in three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	2371***‡	10476***	441588***	272642***	14883***	434607***	286877***	88647***
Rep(Env)	6	97	268	5929***	3484***	205***	5570***	4085**	2075***
Sp	16	1068***	3707***	187879***	110284***	8247***	188690***	191286***	96168***
Env x Sp	32	198***	656***	9480***	5311***	363***	8038***	8259***	2978***
Error	96	86	267	1198	687	48	1132	1020	492
CV, %		12	15	11	11	16	4	4	3

† Env=Environment, Rep=Replicate, Sp= Species.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.8. Mean forage quality of brassica cover crop roots averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

Species/cultivar	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
	$g\ kg^{-1}$							
Turnip								
Appin	86	126	247	192	30	849	863	793
New York	85	121	221	172	25	877	888	800
Rack	76	105	252	193	29	854	864	800
Pointer	76	111	252	194	29	854	866	800
Purple Top	86	123	243	188	28	863	876	796
Barkant	71	97	218	168	22	887	898	820
Forage rape								
Barnapoli	54	71	571	437	96	536	543	605
Dwarf Essex	67	94	405	307	60	709	711	734
Hybrids								
Winfred	64	86	412	313	63	697	700	729
Pasja	82	122	259	198	32	843	853	794
Hunter	81	122	261	200	33	839	850	792
T-Raptor	83	125	264	202	34	836	844	789
Vivant	83	123	253	194	31	847	858	795
Radish								
Daikon	85	125	216	167	23	887	899	807
Graza	80	121	225	173	27	866	877	808
Groundhog	85	125	219	170	23	884	898	808
E. cabbage[†]								
Corine	52	63	734	567	133	357	370	409
LSD[‡] (0.05)	14	25	94	70	18	86	87	52

[†] E. cabbage = Ethiopian cabbage.

[‡] LSD= Least significant difference used as mean separation method, with a probability of 0.05.

[§] Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

4.4.3. Sowing date effect on brassica cover crops forage yield and quality

The analysis of variance and mean squares for brassica cover crop tops, roots, top + root biomass yield and the total N of the biomass yield, for different sowing dates (SD) combined across three environments (Fargo 2014 and Prosper 2013 and 2014), are presented in Table 4.9. The interaction species by SD was significant for all the parameters evaluated. The SD main effect was significant only for root and top + root biomass yield, and root total N. The species main effect was significant for all parameters evaluated except tops total N and total N of biomass yield.

The top biomass yield was higher in the hybrid cv. Pasja with 4.0 Mg ha^{-1} (Table 4.10). In SD2, radish cv. Daikon had the lowest yield with 1.9 Mg ha^{-1}. The effect of SD was significant only in radish and the hybrid, with higher biomass yield in SD1 for both crops. The root yield was higher in turnip cv. Purple Top with 1.9 Mg ha^{-1}, which was significantly higher to all other yields except radish cv. Daikon in SD1. The total biomass yield (top + root) had significant differences across the SDs for turnip, radish, and hybrid, but not for forage rape. The SDs had effect on turnip, radish, and hybrid with higher yield in SD1compared with SD2. The highest yield was in hybrid cv. Pasja with 4.7 Mg ha^{-1} in SD1, which was different with forage rape in SD1 and all the yields in SD2.

Other authors have also reported that early fall sowing dates increase biomass yield (Balkcom et al., 2007; Weil et al., 2009; Villalobos and Brummer, 2013). Radish yield was more sensitive to a delay in sowing date than forage rape. Weil et al., (2009) reported this same trend, indicating sowing date is more critical in forage radish than rapeseed, in the mid-Atlantic, allowing the crop to take up significant amounts of soil N before it is frost-killed. Radish is frost tolerant but several continuous nights with -5°C can kill it, which can make a difference in total forage production by November (Weil et al., 2009). Radish grows best when planted from late July to early September but significant amounts of N can be captured by it when planted as late as 1 October (Weil et al., 2009). In the southern Great Lakes Region, optimum sowing date for mustard is recommended from 13 to 23 August for optimal growth and no later than early September for adequate stands (Björkman et al., 2015). Delaying the sowing date reduces dry matter yield accumulation during the fall and early winter (Villalobos and Brummer, 2013).

The top total N in hybrid cv. Pasja was 95 kg N ha^{-1}, which was higher than in turnip and forage rape in SD1 and radish and hybrid in SD2 (Table 4.11). Root total N was higher in turnip and radish in SD1 with 31 and 32 kg N ha^{-1}, respectively, which were higher than forage rape and hybrid in SD1 and all species in SD2. The higher total biomass yield N was in radish and hybrid with 106 and 107 kg N ha^{-1}, respectively. The SD effect was clear in radish and the hybrid where the total N in SD1 was significantly higher than the total N in SD2. A higher total N is related directly to forage yield, thus delaying the sowing date decreased N accumulation in all species, especially in radish.

The analysis of variance for top quality components in different sowing dates (SD) combined across three environments (Fargo 2014 and Prosper 2013 and 2014), are presented in Table 4.12. The interaction species by SD and the SD main effect were not significant for any components evaluated. The species main effect was significant in all quality components except ADF.

Table 4.9. Analysis of variance and mean squares for brassica cover crop tops, roots, top+root yield, and total N for sowing date (SD) in three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Top yield[§]	Root yield	Top + root yield	Top total N	Root total N	Total biomass yield N[¶]
Env[†]	2	11295	992	18278*	2653	103	3581
Rep(Env)	6	1109	32	1137	1770	9	1929
SD	1	4483	7474*	23533*	624	1597*	4224
Env x SD	2	316	178	912	311	19	390
Env x SD x Rep	6	685*[‡]	111	659	1031*	30	1104*
Sp	3	3935**	3745**	2619*	720	1346***	248
Env x Sp	6	342	232	522	489	43	650
SD x Sp	3	1493*	879**	2149*	1603*	254*	1873*
Env x SD x Sp	6	231	68	335	283	31	372
Error	36	248	58	330	366	15	430
CV, %		18	27	16	26	24	24

[†] Env=Environment, Rep=Replicate, Sp= Species.
[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean squares values in columns 1-3 were divided by 1000, but not columns 4, 5, and 6.
[¶] Total biomass yield N = total N by tops + root.

Table 4.10. Mean biomass yield of brassica cover crop tops, roots, and top + root in four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Top yield			Root yield			Top + root yield		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	-----------	-----------	-----------	-----------	Mg ha^{-1}	-----------	-----------	-----------	-----------
Turnip	2.7	2.7	2.7	1.9	0.8	1.3	4.5	3.5	4.0
F. rape[†]	2.7	2.7	2.7	0.6	0.4	0.5	3.3	3.1	3.2
Radish	2.7	1.9	2.3	1.8	0.7	1.3	4.4	2.6	3.5
Hybrid	4.0	2.8	3.4	0.7	0.3	0.5	4.7	3.2	3.9
Mean	3.0	2.5		1.2	0.6		4.2	3.1	
LSD[‡] (0.05), SD	NS			NS			NS		
LSD (0.05), Sp	NS			NS			NS		
LSD (0.05), SDxSp									
SDxSp[1]	0.6			0.4			0.8		
SDxSp[2]	0.6			0.4			0.8		
SDxSp[3]	0.6			0.5			0.9		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp[1] to compare species means within a same SDs; SDxSp[2] to compare SD means within the same species, and SDxSp[3] to compare different SDs means between different species means.

[§] Targeted days SD1 = August 1; SD2 = August 15.

Table 4.11. Mean total N of brassica cover crop tops, roots and tops + roots in four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Tops total N			Roots total N			Tops + roots total N		
Species	SD1§	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	------------------------------				kg ha^{-1}		------------------------------		
Turnip	62	72	67	31	16	23	93	88	90
F. rape†	71	80	75	8	7	8	79	87	83
Radish	74	61	68	32	15	23	106	76	91
Hybrid	95	66	80	12	7	9	107	72	89
Mean	75	70		21	11		96	81	
LSD‡ (0.05), SD	NS			NS			NS		
LSD (0.05), Sp	NS			NS			NS		
LSD (0.05), SDxSp									
SDxSp[1]	23			7			26		
SDxSp[2]	20			6			22		
SDxSp[3]	23			7			26		

† F. rape = Forage rape.

‡ LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp[1] to compare species means within a same SDs; SDxSp[2] to compare SD means within the same species, and SDxSp[3] to compare different SDs means between different species means.

§ Targeted days SD1 = August 1; SD2 = August 15.

Table 4.12. Analysis of variance and mean squares of forage quality components of brassica cover crops for two sowing dates (SD) in three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	20237**‡	10093	15860*	3044*	785	1480*	2447*	24922**
Rep(Env)	6	189	1138	345*	171	88	101	177	167
SD	1	85	6593	1275	624	430	98	0.07	34
Env x SD	2	186	792	285	86	45	25	6	115
Env x SD x Rep	6	131	1448**	78	143	98**	36	59	127
Sp	3	21135***	8368*	4102**	1541	433*	2773**	799**	26463***
Env x Sp	6	192	1134*	396	358	73*	177	41	274
SD x Sp	3	310	669	162	55	36	73	46	290
Env x SD x Sp	6	103	253	414	121	16	57	37	161
Error	36	264	431	284	113	23	94	67	332
CV, %		10	12	8	6	11	1	1	2

† Env=Environment, Rep=Replicate, Sp= Species.

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

The ash and CP content was higher in radish cv. Daikon, with a mean of 195 and 197 g kg^{-1}, respectively (Table 4.13). The NDF was higher in radish with 233 g kg^{-1}, which was significantly higher than forage rape and the hybrid, and similar with turnip. The ADL was higher in hybrid and turnip with 47.8 and 45.5 g kg^{-1}, respectively (Table 4.14). The IVDMD and NDFD were higher in the hybrid with 918 and 946 g kg^{-1}, respectively, both significantly higher than turnip and radish (Table 4.14 and 4.15). The TDN had the higher value in forage rape with 801 g kg^{-1}, which was higher than all other species evaluated (Table 4.15).

The analysis of variance for root quality components in different sowing dates (SD) combined across three environments, Fargo 2014 and Prosper 2013 and 2014, are presented in Table 4.16. The interaction species by SD was not significant for any the components evaluated. The SD main effect was only significant for ADL and species main effect was significant for all parameters except ash and CP. The NDF, ADF, and ADL were lower in radish cv. Daikon which were different with forage rape, but similar with turnip and hybrid (Table 4.17 and 4.18). The ADL content was affected by SDs, where ADL was significantly lower in SD1 than SD2, with a mean of 37.7 and 41.2 g kg^{-1}, respectively. The IVDMD and NDFD in turnip, radish, and the hybrid were higher than 831 and 838 g kg^{-1}(Table 4.18 and 4.19). The TDN was higher in turnip, radish, and hybrid with 789, 795 and 794 g kg^{-1}, respectively, (Table 4.19).

Table 4.13. Mean forage quality (Ash, CP, and NDF) for brassica cover crop tops of four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Ash			CP			NDF		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	$g\ kg^{-1}$								
Turnip	169	181	175	144	166	155	220	216	218
F. rape[†]	116	120	118	163	187	175	205	196	200
Radish	201	193	197	181	209	195	241	225	233
Hybrid	180	180	180	146	147	147	206	201	203
Mean	167	169		158	178		218	209	
LSD[‡] (0.05), SD	NS			NS			NS		
LSD (0.05), Sp	11			28			16		
LSD (0.05), SDxSp	NS			NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

Table 4.14. Mean forage quality (ADF, ADL, and IVDMD) for brassica cover crop tops of four species and two sowing dates (SD) combined across three environments, Fargo 2014 and Prosper, ND, 2013 and 2014.

	ADF			ADL			IVDMD		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	----------	----------	----------	----------	g kg^{-1}	----------	----------	----------	----------
Turnip	167	162	164	48.0	43.0	45.5	902	899	900
F. rape[†]	164	159	162	46.0	39.4	42.7	908	908	908
Radish	184	173	178	40.0	32.9	36.4	892	885	889
Hybrid	158	155	157	48.2	47.3	47.8	917	918	918
Mean	168	162		45.6	40.7		905	903	
LSD[‡] (0.05), SD	NS			NS			NS		
LSD (0.05), Sp	NS			6.9			11		
LSD (0.05), SDxSp	NS			NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

Table 4.15. Mean forage quality (NDFD and TDN) for brassica cover crop tops of four species and two sowing dates (SD) combined across three environments, Fargo 2014 and Prosper, ND, 2013 and 2014.

	NDFD			TDN		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean
	g kg^{-1}					
Turnip	935	933	934	741	729	735
F. rape[†]	941	945	943	802	801	801
Radish	934	931	932	709	716	713
Hybrid	946	946	946	735	735	735
Mean	939	939		747	745	
LSD[‡] (0.05), SD	NS			NS		
LSD (0.05), Sp	5			14		
LSD (0.05), SDxSp	NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

Table 4.16. Analysis of variance and mean squares of forage quality components of brassica cover crop roots of four species and two sowing date (SD) combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	3962*‡	3122	291978**	175129**	8303**	289415**	179055**	32053*
Rep(Env)	6	46	89	234	156	12	284	228	205
SD	1	1369	6555	6013	3417	217*	4005	2791	2781
Env x SD	2	108	948	434	228	6	254	235	156
Env x SD x Rep	6	57	138	558	341	29	657	596	250
Sp	3	569	1584	132781**	74512**	5928**	129724**	139948**	32315**
Env x Sp	6	154	436*	13164*	7312*	497*	10727*	10968*	2488*
SD x Sp	3	91	149	4178	2440	195	4673	4124	1180
Env x SD x Sp	6	54	53	1798*	1014*	62*	1441*	1431**	406
Error	36	44	106	541	308	23	511	423	223
CV, %		8	9	8	8	12	3	3	2

† Env=Environment, Rep=Replicate, Sp= Species (forage brassica species and cultivars).

‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.17. Mean forage quality (Ash, CP, and NDF) for brassica cover crop roots of four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Ash			CP			NDF		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	---				$g\ kg^{-1}$				---
Turnip	80	94	87	106	133	119	231	259	245
F. rape[†]	69	80	74	91	110	101	436	409	422
Radish	82	87	84	115	128	122	226	261	243
Hybrid	76	81	79	105	124	114	249	285	267
Mean	77	85		104	124		285	304	
LSD[‡] (0.05), SD	NS			NS			NS		
LSD (0.05), Sp	NS			NS			94		
LSD (0.05), SDxSp	NS			NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

Table 4.18. Mean forage quality (ADF, ADL, and IVDMD) for brassica cover crop roots of four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	ADF			ADL			IVDMD		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean	SD1	SD2	Mean
	---------------------				g kg^{-1}				---------------------
Turnip	179	202	191	25.7	33.6	29.6	873	837	855
F. rape[†]	333	312	322	69.4	63.2	66.3	665	698	682
Radish	174	202	188	23.9	31.1	27.5	879	845	862
Hybrid	192	217	204	31.9	36.9	34.4	841	820	831
Mean	219	233		37.7	41.2		815	800	
LSD[‡] (0.05), SD	NS			2.4			NS		
LSD (0.05), Sp	70			18.2			85		
LSD (0.05), SDxSp	NS			NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

Table 4.19. Mean forage quality (NDFD and TDN) for brassica cover crop roots of four species and two sowing dates (SD) averaged across three environments, Fargo 2014 and Prosper 2013 and 2014.

	NDFD			TDN		
Species	SD1[§]	SD2	Mean	SD1	SD2	Mean
	-------------------	-------------------	-------------------	g kg^{-1}	-------------------	-------------------
Turnip	881	847	864	802	777	789
F. rape[†]	668	700	684	703	714	708
Radish	888	856	872	806	785	795
Hybrid	845	830	838	801	787	794
Mean	821	808		778	765	
LSD[‡] (0.05), SD	NS			NS		
LSD (0.05), Sp	85			41		
LSD (0.05), SDxSp	NS			NS		

[†] F. rape = Forage rape.

[‡] LSD at 0.05 of significance. SD to compare among SD means averaged across species; Sp to compare among species means averaged across SDs; SDxSp to compare different species means and SD means.

[§] Targeted days SD1= August 1; SD2= August 15.

4.4.4. Plant density effect on forage yield and quality of forage brassicas

The analysis of variance for brassica cover crop tops, roots, top + root biomass yield and total N of different plant densities (PD) combined across three environments (Fargo 2014 and Prosper 2013 and 2014), are presented in Table 4.20. The interaction of species by PD was not significant for any the parameter evaluated. Plant density was significant for tops, top + root biomass yield and tops total N. The plant density effect was positive due to the targeted plant density was closer to the final plant density determined at harvest time (Table 4.24). The species was significant for top and root yield and total root N.

The highest plant density (PD4) had the highest yield (3.0 Mg ha^{-1}) and total N (79 kg N ha^{-1}), which was significantly different from PD1 and PD2 and similar with PD3 (Table 4.21). The root biomass yield (1.4 Mg ha^{-1}) and total N (26 kg N ha^{-1}) was highest in turnip (Table 4.22). The PDs were significant in total biomass yield (tops + roots), with the highest yield for PD4 with 3.9 Mg ha^{-1} (Table 4.23).

The analysis of variance for top quality components of brassica cover crops, in different plant densities (PD) combined across three environments (Fargo 2014 and Prosper 2013 and 2014), are presented in Table 4.25. The interaction of species by PD was not significant for any of the components evaluated. The PD main effect was only significant for ash content, while species main effect was significant in all quality components evaluated.

The ash content was higher at PD4 with 174 g kg^{-1}, which was different from PD1 and PD2 but similar to PD3 (Table 4.26). Additionally, radish was the species with the higher ash content compared with turnip and hybrid. The highest ash content was 180 g kg^{-1}. The CP content was higher in radish roots with 189 g kg^{-1}, which was different with turnip and hybrid. The NDF and ADF were highest for radish cv. Daikon, with contents of 231 and 183 g kg^{-1}, respectively (Table 4.27). The hybrids had the lowest fiber content with 209 and 160 g kg^{-1} of NDF and ADF, respectively. The lowest content of ADL was in radish with 39.7 g kg^{-1}, (Table 4.28). The hybrids had the highest digestibility with 906 and 937 g kg^{-1} for IVDMD and NDFD, respectively (Table 4.28 and 4.29). The TDN was higher in turnip and hybrids with 747 g kg^{-1}, which were different with radish (Table 4.29).

The analysis of variance for root quality components of brassica cover crops, for different plant densities (PD) combined across three environments (Fargo 2014 and Prosper 2013 and 2014), are presented in Table 4.30. The interaction of species by PD and the species main effect were not significant for any of the components evaluated. The PD main effect was significant for all quality components except ash and CP content.

The ash and CP content were not significant between plant densities (Table 4.31). The NDF, ADF and ADL were higher in PD4 with 284, 221, and 37.5 g kg^{-1}, which were always significantly higher than PD1 and PD2, but equal to PD3 (Table 4.32 and 4.33). The IVDMD and NDFD were always higher in PD1, with 856 and 867 g kg^{-1}, respectively (Table 4.33 and 4.34). The TDN was also higher in PD1 with 802 g kg^{-1}, which was different with PD3 and PD4 but similar to PD2 (Table 4.34).

Table 4.20. Analysis of variance and mean squares for root, tops+roots N total in a plant density (PD) study in three environments, Fargo, 2014 and Prosper, ND, in 2013 and 2014.

Source of variation	df	Top yield	Root yield	Top+root yield	Top total N	Root total N	Total biomass N[¶]
Env[†]	2	45634*[‡]	9877*	97810**	44824*	3277*	72339*
Rep(Env)	6	5890**	123	6048**	4894	48	5041
PD	3	8725**	435	5540*	7169*	38	6244
Env x PD	6	838	369	1095	1207	74	1394
Env x PD x Rep	18	999**	115	1440*	1868***	40	2278***
Sp	2	2384*	6975*	1207	1384	2646*	3753
Env x Sp	4	136	923**	671	344	266*	959
PD x Sp	6	340	234	1008	327	79	703
Env x PD x Sp	12	437	151	719	441	52	633
Error	48	344	102	640	311	36	483
CV, %		26	30	24	28	30	27

[†] Env=Environment, Rep=Replicate, Sp= Species.

[‡] *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

[§] Mean squares values in columns 1-3 were divided by 1000, but not columns 4, 5, and 6.

[¶] Total biomass N = Total N of tops + roots.

Table 4.21. Mean biomass yield and total N of tops of three species and four plant densities (PD) averaged across three environments, in Fargo 2014 and Prosper, ND, in 2013 and 2014.

	Top yield					Top total N				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	---------Mg ha^{-1}---------					---------kg ha^{-1}---------				
Turnip	1.6	1.7	2.2	2.7	2.1	48	45	66	69	57
Radish	1.5	2.1	2.4	2.7	2.2	48	65	79	85	69
Hybrid	1.8	2.1	2.9	3.5	2.6	41	49	78	84	63
Mean	1.7	2.0	2.5	3.0		46	53	74	79	
LSD† (0.05), PD	0.6					23				
LSD (0.05), Sp	0.2					NS				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1= 44 plants m^{-2}; PD2 =66 plants m^{-2}; PD3= 133 plants m^{-2}; PD4 ≥ 200 plants m^{-2}.

Table 4.22. Mean biomass yield and total root N of three species and four plant densities (PD) averaged across three environments, in Fargo 2014 and Prosper, ND in 2013 and 2014.

	Root yield					Root total N				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	------------------------Mg ha^{-1}--------------------------					------------------------------kg ha^{-1}------------------------				
Turnip	1.8	1.4	1.2	1.2	1.4	32	25	23	22	26
Radish	1.2	1.3	1.1	1.1	1.2	23	26	23	24	24
Hybrid	0.6	0.6	0.5	0.6	0.6	10	9	10	11	10
Mean	1.2	1.1	1.0	1.0		21	20	19	19	
LSD† (0.05), PD	NS					NS				
LSD (0.05), Sp	0.6					11				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1= 44 plants m^{-2}; PD2 =66 plants m^{-2}; PD3= 133 plants m^{-2}; PD4 $\geq$ 200 plants m^{-2}.

Table 4.23. Mean biomass yield and total N of tops + roots of three species and four plant densities (PD) averaged across three environments in Fargo 2014 and Prosper 2013 and 2014.

	Top + root yield					Top + root total N				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	---------------------------Mg ha^{-1}----------------------					-----------------------------kg ha^{-1}-------------------------				
Turnip	3.5	3.1	3.4	3.8	3.5	80	70	89	91	82
Radish	2.8	3.4	3.5	3.9	3.4	71	91	103	109	93
Hybrid	2.4	2.7	3.4	4.0	3.1	51	58	87	95	73
Mean	2.9	3.1	3.4	3.9		67	73	93	98	
LSD† (0.05), PD	0.7					NS				
LSD (0.05), Sp	NS					NS				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1= 44 plants m^{-2}; PD2= 66 plants m^{-2}; PD3= 133 plants m^{-2}; PD4 >200 plants m^{-2}.

Table 4.24. Species/cultivars and final plant density of cover crops at harvest time at Fargo and Prosper, ND, in 2013 and 2014.

Species/cultivar	PD1†	PD2	PD3	PD4
	--plants m^{-2}--			
Turnip	44	70	78	251
Radish	38	66	60	112
Hybrid	44	65	105	217

† Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 > 200 plants m^{-2}.

Table 4.25. Analysis of variance and mean squares of forage quality components of brassica cover crop tops for plant density (PD) in three environments, Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Ash	CP§	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env†	2	3232	13567*	19906***	479	1332*	3694*	5565**	4756
Rep(Env)	6	464	664	284	116	45	40	166	329
PD	3	794*‡	1016	139	41	56	205	20	677
Env x PD	6	143	1538	388	129	85	200	229	194
Env x PD x Rep	18	230**	1089***	172	98	53***	143*	147*	282**
Sp	2	4901**	14824**	4859*	4797*	637*	9940**	3093*	6421**
Env x Sp	4	177	625	304	397*	43	369*	210*	182
PD x Sp	6	164	299	96	39	23	46	55	151
Env x PD x Sp	12	118	323	107	81	16	80	64	147
Error	48	94	242	124	68	12	68	69	108
CV, %		6	9	5	5	8	1	1	1

† Env=Environment, Rep=Replicate, Sp= Species.
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.26. Mean forage quality (Ash and CP) for brassica cover crop tops of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Ash					CP				
Species	PD1[‡]	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	-----------------					g kg^{-1} -----------------				
Turnip	150	158	160	163	158	168	157	169	153	162
Radish	176	182	178	184	180	179	187	199	189	189
Hybrid	158	157	163	176	164	143	145	158	149	149
Mean	161	165	167	174		163	163	175	164	
LSD[†] (0.05), PD	8					NS				
LSD (0.05), Sp	9					16				
LSD (0.05), PDxSp	NS					NS				

[†] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[‡] Targeted PD1= 44 plants m^{-2}; PD2= 66 plants m^{-2}; PD3= 133 plants m^{-2}; PD4 ≥200 plants m^{-2}.

Table 4.27. Mean forage quality (NDF and ADF) for brassica cover crop tops of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	NDF					ADF				
Species	PD1[‡]	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	g kg^{-1}									
Turnip	227	222	224	223	224	172	168	173	173	172
Radish	236	234	227	228	231	183	184	182	185	183
Hybrid	208	211	204	212	209	158	162	159	163	160
Mean	224	222	218	221		171	171	171	174	
LSD[†] (0.05), PD	NS					NS				
LSD (0.05), Sp	11					13				
LSD (0.05), PDxSp	NS					NS				

[†] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[‡] Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 $\geq$200 plants m^{-2}.

Table 4.28. Mean forage quality (ADL and IVDMD) for brassica cover crop tops of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	ADL					IVDMD				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	-----------------------g kg^{-1}-----------------------									
Turnip	42.6	44.6	43.1	47.4	44.4	885	888	881	884	885
Radish	41.7	40.4	37.0	39.7	39.7	876	874	869	872	873
Hybrid	48.9	49.3	45.8	48.3	48.1	911	905	904	903	906
Mean	44.4	44.8	42.0	45.1		891	889	885	887	
LSD† (0.05), PD	NS					NS				
LSD (0.05), Sp	4.3					13				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 ≥200 plants m^{-2}.

Table 4.29. Mean forage quality (NDFD and TDN) for brassica cover crop tops of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	NDFD					TDN				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	----------------------------------g kg^{-1}----------------------------------									
Turnip	922	925	919	920	921	754	749	743	742	747
Radish	919	923	919	922	921	727	722	726	721	724
Hybrid	939	935	938	937	937	753	753	748	735	747
Mean	927	927	925	927		744	741	739	733	
LSD† (0.05), PD	NS					NS				
LSD (0.05), Sp	10					9				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 ≥200 plants m^{-2}.

Table 4.30. Analysis of variance and mean squares of forage quality components of brassica roots in a plant density (PD) study in Fargo 2014 and Prosper 2013 and 2014.

Source of variation	df	Ash	CP[§]	NDF	ADF	ADL	IVDMD	NDFD	TDN
Env[†]	2	126	1208	411581***	242697***	14860***	404464***	267846***	71337*
Rep(Env)	6	149	524	1038	570	27	884	655	72
PD	3	291	1674	7616*	4993*	399*	10076**	6891**	2620*
Env x PD	6	98	363	1062	594	44	664	585	295
Env x PD x Rep	18	102***[‡]	306***	718	472	45	1012	824	523**
Sp	2	1219	6362	951	182	144	3194	4602	696
Env x Sp	4	1906***	5638***	5502***	2757**	192**	4531**	4092***	1091*
PD x Sp	6	7	55	1165	621	24	551	455	151
Env x PD x Sp	12	72**	237**	496	308	23	471	366	243
Error	48	22	80	808	482	31	809	737	205
CV, %		6	7	11	11	17	3	3	2

† Env=Environment, Rep=Replicate, Sp= Species (forage brassica species and cultivars).
‡ *, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.
§ Forage quality components: Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), neutral detergent fiber digestibility (NDFD) and total digestible nutrients (TDN).

Table 4.31. Mean forage quality (Ash and CP) for brassica roots of three species and four plant densities (PD) combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	Ash					CP				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	---------------------------					g kg^{-1}---------------------------				
Turnip	78	81	83	84	82	106	114	117	121	114
Radish	84	87	91	93	89	125	131	140	146	136
Hybrid	74	76	79	82	78	104	105	115	121	111
Mean	79	81	84	86		112	117	124	129	
LSD† (0.05), PD	NS					NS				
LSD (0.05), Sp	NS					NS				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1= 44 plants m^{-2}; PD2= 66 plants m^{-2}; PD3= 133 plants m^{-2}; PD4 ≥200 plants m^{-2}.

Table 4.32. Mean forage quality (NDF and ADF) for brassica roots of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	NDF					ADF				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	g kg^{-1}									
Turnip	249	257	272	278	264	192	199	211	215	204
Radish	251	264	274	268	264	195	205	214	212	207
Hybrid	241	259	285	307	273	185	197	220	235	209
Mean	247	260	277	284		191	200	215	221	
LSD† (0.05), PD	22					16				
LSD (0.05), Sp	NS					NS				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 = >200 plants m^{-2}.

Table 4.33. Mean forage quality (ADL and IVDMD) for brassica roots of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	ADL					IVDMD				
Species	PD1[‡]	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	$g\ kg^{-1}$									
Turnip	27.3	29.8	32.6	34.3	31.0	864	851	836	829	845
Radish	30.1	33.2	35.7	36.7	33.9	849	834	819	815	829
Hybrid	29.0	31.6	37.3	41.4	34.8	855	847	814	797	828
Mean	28.8	31.5	35.2	37.5		856	844	823	814	
LSD[†] (0.05), PD	4.4					17				
LSD (0.05), Sp	NS					NS				
LSD (0.05), PDxSp	NS					NS				

[†] LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

[‡] Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 = >200 plants m^{-2}

Table 4.34. Mean forage quality (NDFD and TDN) for brassica roots of three species and four plant densities (PD), combined across three environments, Fargo 2014 and Prosper 2013 and 2014.

	NDFD					TDN				
Species	PD1‡	PD2	PD3	PD4	Mean	PD1	PD2	PD3	PD4	Mean
	--g kg^{-1}					---				
Turnip	876	867	850	847	860	803	795	787	785	793
Radish	863	852	841	839	849	795	788	779	779	785
Hybrid	863	851	825	811	838	808	800	788	776	793
Mean	867	857	839	832		802	794	785	780	
LSD† (0.05), PD	16					11				
LSD (0.05), Sp	NS					NS				
LSD (0.05), PDxSp	NS					NS				

† LSD at 0.05 of significance. PD to compare among PD means averaged across species; Sp to compare among species means averaged across PDs; PDxSp to compare different species means and PD means.

‡ Targeted PD1 = 44 plants m^{-2}; PD2 = 66 plants m^{-2}; PD3 = 133 plants m^{-2}; PD4 = >200 plants m^{-2}.

4.5. Conclusions

Brassica cover crops have an interesting potential for late grazing in North Dakota, due to the high biomass yield and forage quality. In general, biomass yield was higher in tops than roots in all species. Turnip cvs. Appin, Pointer, Barkant ,and Purple Top had the highest above ground biomass yield. Root biomass yield was higher in radishes cvs. Groundhog and Daikon. Forage quality varied among species, cultivars, and with the part of the plant (tops and roots). Crude protein and fiber digestibility were higher in tops, and fiber content was higher in roots. Cover crops with enlarged root (radish, turnip, and some hybrids) have, in general, less fiber in the edible parts of the plants than specieswith thick stems, which confer desirable characteristics to feed livestock.

The first sowing date (9-12 August) had the highest forage yield. Delaying sowing decreased the root biomass yield of species with enlarged root (radish and turnip). However, tops biomass yield did not decrease when sowing date was delayed, except in radish and hybrids. Forage quality was not influenced by sowing date, but was affected by species. Brassica cover crops sown with the purpose of grazing them, should be sown as soon as possible after wheat harvest in North Dakota to optimize forage yield and quality.

The highest plant density evaluated (≥200 plants m^{-2}) produced the highest tops and total forage biomass yield across all species. Root yield was not affected by plant density. Top CP, NDF, and NDFD was similar in all plant densities. Root fiber content increased when plant density increased, but the digestibility of the root fiber decreased when plant density increased.

All forage brassicas can be used as cover crops for grazing in North Dakota, but it is important to know that marked differences in total forage yield exist among species and cultivars within species. Before deciding what forage brassica(s) to select, growers should look at cultivar trials near their location to identify the species and cultivars with the highest potential forage yield and quality.

4.6. Literature Cited

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