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Utilizing a multi-index decision analysis method to overall assess forage yield and quality of C3 grasses in the western Canadian prairies

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ABSTRACT

Seasonal dynamic of forage quality and yield has a major impact on livestock production. A sound evaluation on quality and quantity of forage is useful for cost-effective utilization of forage. However, forage quality and yield can vary with forage species, harvest seasons and yearly climate conditions. To improve forage use efficiency, a field experiment (2008–2010) was conducted in Swift Current, Saskatchewan, Canada. Dry matter yield and quality indicators (fiber, protein, digestibility and minerals) were measured for nine cool-season grasses harvested in June, August and October. The interrelationships and attributes among quality indicators were determined by principal component analysis (PCA) and the weights of quality indicators were calculated by entropy weight (EW) method. To synthesize different attribute indicators into a comprehensive index that reflects quality ranking of different forage species, an integrated multi-index decision analysis method, i.e., PCA-based TOPSIS with EW, was used in this paper. The evaluation process and results showed that the interrelation patterns and positive or negative attributes for quality indicators were consistent with years and harvest seasons, whereas the rankings of most grasses in yield and comprehensive quality varied with years and harvest seasons. According to the yearly and seasonal rankings of forage quality and yield, flexible production tactics and adaptive management techniques should be considered within the western Canadian prairie region. For instance, Northern wheatgrass (*Agropyron dasystachyum*) can be recommended to be mixed with high quality forages due to its high yield in any harvest season. Meadow bromegrass (*Bromus Riparius*) can be recommended to be mixed with high yield forages due to its high quality in summer and fall. These findings will provide valuable information for forage breeders, and livestock and forage managers to maximize grass utilization efficiency while balancing yield and quality.

1. Introduction

Forage quality directly impacts the performance of livestock (Ball et al., 2001). High quality and high-yield forages are the main assets of any livestock operation and are also the foundations of most forage-based rations (Newman et al., 2006). However, both quality and yield of forages varied with forage species and maturity stages at harvest (Bruinenberg et al., 2002; Karn et al., 2006). Knowing the overall rankings of yield and quality for forages harvested in different seasons will help livestock producers select which forage species and supplements to achieve economic optimum livestock performance (Newman et al., 2006). To assess the quality of different forages, many wet chemical analysis methods and technical systems have been developed. They mainly include the detergent fiber analysis evaluation system (Van Soest, 1964), the protein evaluation system (Makkink et al., 1994), the nutrient composition analysis evaluation system (Knudsen, 1997), and the energy analysis evaluation system (Coleman and Moore, 2003). To predict forage quality based on chemical components, prediction methods were proposed based on specific regression equations, such as the relative feed value method and the relative feed quality method (Moore and Undersander, 2002). However, for the chemical analysis methods, quality indicators were studied one by one rather

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than with a holistic or integrative approach. Furthermore, for forage quality prediction methods, the equation parameters varied with forage species, maturity stages and growth environments. Generally, in other studies, forage quality indicators, including crude protein, detergent fiber, digestibility and main minerals, were not synthesized into a comprehensive index to reflect forage quality.

Principal component analysis (PCA) is a nonparametric statistical method and well-established exploratory technique. It can be used to extract relevant important information and to explore underlying changing trends from a multivariate complex data set that may contain unapparent patterns or structure (Yeater et al., 2015). The PCA configuration diagrams can be used to visualize the underlying interrelationship occurring in a data set. The advantage of PCA is that the correlation performance of all variables can be analyzed simultaneously and holistically by extracting the main information from the data set (Kenkel, 2006). Therefore, the PCA method is widely employed in agricultural and ecological fields. For example, to assess the magnitude of genetic improvement in herbage yield and other agronomical traits, the PCA method was used by Sampoux et al. (2011), who revealed the associations among perennial cultivar traits. Papadopoulos et al. (2012) made use of PCA to reveal a strong association between seeded grass growth and dry matter yield, as well as, compatibility among seeded grass species. To determine the influence of forage species combination on protein degradability, Simili Da Silva et al. (2014) used PCA to illustrate the relationship among the complex legume-grass mixtures and among forage quality variates.

Entropy weight (EW) method is an objectively fixed weight method that can quantify the relative importance of each indicator on the target data set by calculating the relative weight of each indicator based on the appraisal matrix information (Hsu and Hsu, 2008). In information theory, the EW represents useful information of the evaluation indicator. The bigger the EW of the indicator, the more useful the information the indicator represents (Hsu and Hsu, 2008). Because the EW method determines weight according to the amount of inherent information of the indicator, it has the advantage of eliminating anthropogenic disturbances and reflecting different roles of indicators in evaluation (Li et al., 2012). Therefore, the EW method is widely used in agricultural and environmental fields. Zhang and Fan (2001) applied the generalized maximum entropy approach to estimate crop-specific production technologies. To balance the demand and supply sides of water resource, a comprehensive entropy weight risk analysis approach was proposed and applied to water source decision-making by Li et al. (2012).

Technique for order of preference by similarity to ideal solution (TOPSIS) is a multi-index decision analysis and evaluation method (Tzeng and Huang, 2011). Its rationale is that based on positive and negative attributes of indicators, the selected alternative should have the shortest geometric distance from the positive-ideal solution and the longest geometric distance from the negative-ideal solution in a geometrical sense (San Cristóbal, 2012). Its advantage is that it can synthesize multiple different attribute indicators into a comprehensive index. To choose optimal fertilization schemes in semi-natural sward, fertilization management alternatives were evaluated by Baležentienė and Klimas (2011) through application of the TOPSIS method. To investigate the effect of irrigation on yield and nutritional quality of Arabica coffee, Liu et al. (2016) established the comprehensive evaluation model by applying the TOPSIS method.

The PCA-based TOPSIS with EW is an integrated multi-index decision analysis method. Its advantage is that it can determine all-around and holistic interrelationships among quality indicators and display the different roles of indicators in the evaluation. More importantly, it can synthesize multiple indicators with different positive or negative attributes and different roles into a comprehensive index of credibility.

In the western Canadian semi-arid prairie region, cool-season (C3) grasses are the major forage types used in ruminant production (Jefferson et al., 2002). Most C3 grasses have common growth patterns and similar photosynthetic and metabolic pathways. However, certain C3 grass species can have distinct yield and quality owing to their different biological and ecological characteristics (e.g., one-time growth and re-growth; long-lived species and short-lived species; native species and tame species), as well as, physiological, morphological and anatomical feature (e.g., resistance and adaptability, leaf-to-stem ratio, botanical structure and chemical composition) (Zhao et al., 2008). In addition, many other factors can also affect forage yield and quality, including soil fertility, insect damage, harvest methods and storage, grazing management, and plant age, etc. (Ball et al., 2001). Among these factors, grass species and growth stages at harvest are the most important affected factors (Fulgueira et al., 2007). To examine the correlation among quality indicators, most studies applied paired Pearson linear correlation coefficient (Ferdinandez and Coulman, 2001; Karn et al., 2006; Zhao et al., 2008). These studies did not consider all quality indicators as a whole to carry out a correlation analysis. To evaluate the inter-species differences in forage yield and quality, previous studies have mostly focused on comparing differences among species, seasons or years for each quality indicator by using variance analysis, without synthesizing multiple important quality indicators into a comprehensive index for holistic contrast analysis. Although a few studies (Zhang and Fan, 2001; Sampoux et al., 2011; Liu et al., 2016) have reported the application of the PCA, EW or TOPSIS method in agriculture and grassland ecology, there is only limited information available on comprehensive quality evaluation for the C3 grass species of interest. The objectives of this study were: (i) to examine the interrelation pattern of quality indicators for C3 grass species over three different harvest seasons and provide the prerequisite to comprehensive evaluation of forage quality; and (ii) to conduct an overall evaluation and identify which of the nine C3 grass species can produce optimal forage yield and quality when grown under the western Canadian environmental conditions by using PCA-based TOPSIS with EW.

2. Materials and methods

2.1. Experimental design and data collection

This research was conducted on an Orthic Brown Chernozemic soil over a three-year period (2008–2010) at the Agriculture and Agri-Food Canada Swift Current Research and Development Centre (AAFC-SCRDC) (lat. 50°25′N, long. 107°44′W, elev. 824 m), Saskatchewan, Canada. The experiment was arranged in a split-plot randomized complete block design (RCBD) with four replications, in which the areas corresponding to three harvest seasons were taken as main plots and the subareas corresponding to nine grass species were taken as subplots. All perennial grasses were seeded on June 2, 2006, at a rate of 98 pure live seeds/m^2 and a depth of 1.3 cm. Each 6.00 m by 1.53 m plot consisted of five seeded rows with a 30.5 cm row spacing. The nine C3 grass species, including Hybrid bromegrass (*Bromus inermis Leyss.* × *B. riparius*; HBG), Meadow bromegrass (*B. riparius*; MBG), Awned wheatgrass (*Agropyron subsecudum*; AWG), Canada wild rye (*Elymus canadensis*; CWR), Western wheatgrass (*Pascopyrum smithii*; WWG), Needle and thread grass (*Hesperostipa comata*; NT), Northern wheatgrass (*A. dasystachyum*; NWG), Green needlegrass (*Nassella viridula*; GNG), and June grass (*Koeleria macrantha*; JG), were selected for this study. Here, HBG and MBG are tame species, and the others are native species.

Forage samples were collected in June, August and October of each study year. Each plot was split into three subplots. Harvest dates were randomly assigned to each subplot and clippings were taken from randomly placed 0.25 m^2 quadrat within each subplot. Only the center rows of the plots were sampled in order to avoid micro environmental effects associated with the outer rows. In October all plots were mowed using a flail plot harvester to a 5 cm stubble height. Forage sub-samples were dried at 50 °C for 48 h in a forced-air oven to a constant weight and then weighed. A sub-sample was collected for the dry matter and forage nutritive value determination. The dry matter yield of each plot was calculated by multiplying the percentage dry matter of the oven-dried sub-sample by the harvested fresh weight of the plot then converted to kilograms per hectare. Dried samples were ground using a Wiley Mill fitted with a 1-mm screen and then were labelled and stored in glass bottles prior to analysis. In the present study, the forage quality indicators included acid detergent fiber (ADF), neutral detergent fiber (NDF), crude protein (CP), organic matter digestibility (OMD), calcium (Ca), and phosphorus (P). Forage nutritive values (i.e., ADF, NDF, CP) were measured as described by Iwaasa et al. (2014), while for forage OMD measurements, bovine rumen fluid was utilized (Schellenberg et al., 2012). Total Kjeldahl nitrogen was determined using the method adopted by Noel and Hambleton (1976) and was multiplied by 6.25 to determine CP (AOAC, 1984). Calcium and P were determined using the methods described by Steckel and Flannery (1968) and Varley (1966), respectively.

2.2. Statistical analysis and evaluation methods

To determine the effects and interactions of grass species, harvest seasons and study years on forage yield and quality, the normality and variance homogeneity of the sample data were checked by the Shapiro-Wilk and Barlett tests (the significance level $\alpha = 0.05$), respectively. A linear mixed-effect model for analysis of covariance (ANCOVA) was performed using the *lmer* function from the R package 'lme4' (Bates et al., 2017). Yearly growing season precipitation and temperature are important meteorological factors driving inter-annual effects, but the precipitation from the previous October to current April of each year, to some extent, also has an impact on inter-annual effects. Therefore, in order to better explain potential effects, non-growing season precipitation from the previous October to current April of each year (i.e., 90.7 mm, 99.0 mm, 129.6 mm in 2008, 2009, and 2010, respectively) were considered as covariates in ANCOVA. Meanwhile, grass species, harvest seasons, study years and their interactions were treated as fixed effects in mixed-effects models, while block (replication), block × year, and block × year × harvest season were treated as random effects in ANCOVA. To better clarify and visualize potential interrelationships among forage quality indicators, PCA for six quality indicators (i.e., ADF, NDF, OMD, CP, Ca and P) was carried out using the *PCA* function from the R package 'FactoMineR' (Husson et al., 2017). To quantify the relative importance of each quality indicator in the evaluation, the EW of indicators were calculated using the *entropy* function from the R package 'entropy' (Hausser et al., 2012). To conduct a credible evaluation on forage quality according to all useful information assembled by the PCA and EW methods, a PCA-based TOPSIS with EW was adopted by utilizing the *topsis* function from the R package 'topsis' (Mahmoud, 2015). To test the stability and reliability of the evaluation results, the discrimination degrees were calculated according to mathematical formula proposed by Yu et al. (2008) in the R language environment. Based on relative comprehensive quality scores and dry matter yields of all the nine C3 grass species, two-dimensional scatter distribution diagrams of forage yield and quality evaluation were developed using the basic R package 'graphics' (R Core Team, 2017).

3. Results

3.1. Climatic condition

Over the three years of this study, the annual precipitation and its monthly and seasonal distribution pattern among the growing seasons (May to September) were different for each year. In 2008, rainfall was higher than the long-term average and was relatively concentrated in late spring and early summer, and the temperature was closer to the long-term average than other years (Fig. 1A). Non-growing season precipitation was marginally less than the long-term average, whereas growing season precipitation was higher than the long-term average (Fig. 1B). Overall, the year of 2008 provided relatively good moisture and growing conditions for the grasses, and it could be considered a wet year compared to the long-term average. In 2009, the monthly precipitation was generally less than the long-term average from April to July, and the temperature differences were relatively large in spring and fall (Fig. 1A). Precipitation in both the non-growing and growing seasons was less than the long-term average, and it could be considered to be a dry year compared to the long-term average. (Fig. 1B). In 2010, most of the monthly precipitation values were higher than their respective long-term averages, and air temperature was nearly average during the growing season (Fig. 1A). Moreover, precipitation in both the non-growing and growing seasons was higher than the long-term average, especially in the growing season, which had almost double the long-term average. Thus, 2010 could be considered a wet year compared to the long-term average (Fig. 1B). Generally, air temperatures during the study years were similar among growing seasons except for September and October of 2009, but the precipitation pattern varied largely from year to year, which resulted in different moisture conditions among growing seasons within the three study years. These changes in moisture and growing conditions during the three-year period provide the meteorological basis for later explanation of the evaluation on forage yield and quality.

3.2. Covariance analysis

The results of ANCOVA showed that the effects of year, harvest season, species and year × species on all variables were significant ($P < 0.05$). Similarly, the effects of year × harvest season on all variables except OMD, the effects of harvest season × species on all variables except P, and the effects of year × harvest × species on all variables except CP were significant ($P < 0.05$). Generally, all of the main effects and most of the interactive effects of year, harvest season and species on forage yield and quality indicators were significant ($P < 0.05$) (Table 1).

3.3. Change of forage yield and quality indicators

The scatter diagrams with ± standard error (SE) bar for yield and each quality indicator in the different harvest seasons over the three-year period are presented in Fig. 2, in order to more intuitively understand their variability with year and harvest season. The results showed that the inter-species variation and the inter-seasonal variation in dry matter yield were different in each year. Yields of each grass in summer and fall were similar and consistently higher than that in spring in 2008 and 2010, whereas in 2009 yields of each grass were closely similar in the three harvest seasons. The value of ADF and NDF were similar, and both were higher in summer and fall than in spring, while the value of CP, OMD and P were similar and consistently lower in summer and fall than in spring regardless of study year. However, the value of Ca exhibited great inter-seasonal and inter-species fluctuation, and no consistent trend with season advancing was observed over the three years (Fig. 2). These scatter diagrams reflecting the variations of yield and quality indicators would facilitate the explanation of the overall assessment results of quality and yield for the nine C3 grasses.

3.4. Interrelation pattern among forage quality indicators

To determine the positive or negative attributes of indicators in the evaluation of forage comprehensive quality, the interrelationships among quality indicators were analyzed using PCA and the results are shown in Fig. 3. The accumulated contributions of both PC1 and PC2 in the PCA diagrams were consistently more than 70%. The interrelationships among quality indicators presented similar and relatively stable patterns for the three different harvest seasons in all three years. Based on the PCA diagrams (Fig. 3), both ADF and NDF were consistently negatively correlated with all other quality indicators for each harvest season. Especially NDF was strongly negatively correlated with

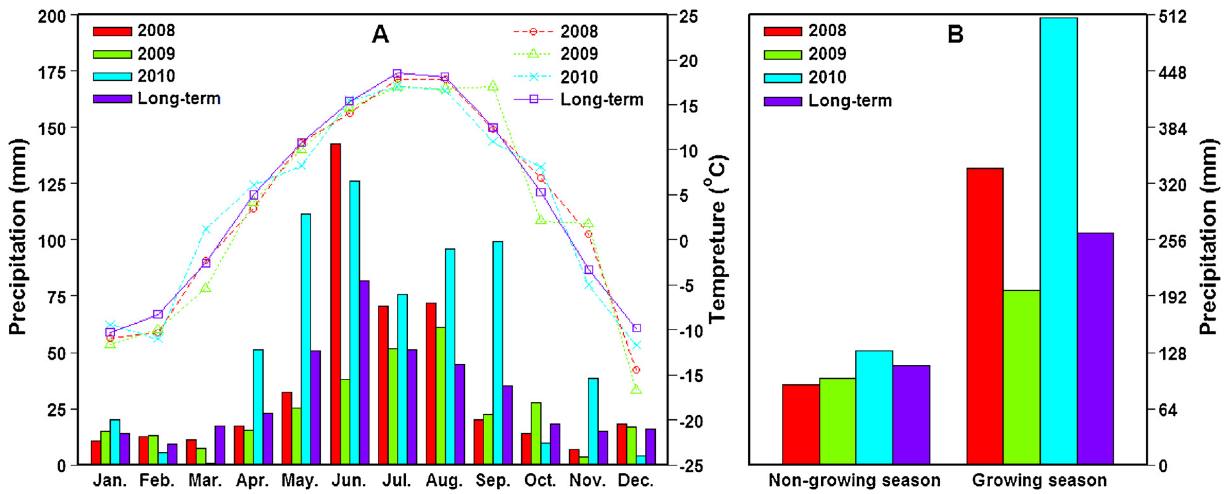

Fig 1. The monthly mean precipitation (bars) and air temperature (lines), precipitation of non-growing season (from previous October to current April) and growing season (from May to September) during 2008–2010 and the long-term (30 years) average at the Swift Current meteorological station, Canada.

OMD based on the first two principal components. There were positive correlations between ADF and NDF, between OMD and Ca, and between P and CP for the nine C3 grass species. The positive correlations between ADF and NDF were consistent for the three harvest seasons over the three-year period. The positive relationships between Ca and OMD for C3 grasses harvested in spring and summer were stronger in both 2008 and 2010 (wet years) than in 2009 (dry year). The positive correlations between P and CP for all C3 grasses harvested in summer were consistent from year to year, whereas the correlations in spring were stronger in 2009 than in 2008 and 2010. No pronounced association of Ca with either CP or P was found in any harvest season over the three-year period (Fig. 3).

3.5. Evaluation results of PCA-based TOPSIS with EW

Using the PCA-based TOPSIS with EW, the EW of the six forage quality indicators in the comprehensive evaluation were calculated to reflect the different role of each indicator in the evaluation (Eq. A.(1)–(2); Table A1). According to the positive and negative attributes of indicators determined from the PCA-based correlation pattern among the six quality indicators, the comprehensive relative quality scores and ranks of the nine C3 grasses were obtained by using the PCA-based TOPSIS with EW (Eq. A. (1)–(8); Tables A2–A10). To test the stability and reliability of the evaluation results, the discrimination degree was calculated for each evaluation result (Eq. B. (1); Table A11). The discrimination degree test demonstrated that all of the evaluation results were reasonable and reliable in the study (Table A11). The two-dimensional scatter distribution diagrams of comprehensive quality and yield for the nine C3 grass species were drawn using R software to present a visualized overall assessment result simultaneously considering yield and quality (Fig. 4).

In terms of yield for all harvest seasons, in 2008, MBG and NWG were above average, while JG, NT and WWG were below average; in 2009, HBG, GNG, NT and NWG were above average, while AWG, CWR and JG were below average; in 2010, NWG, MBG and WWG were above average, while AWG, CWR, GNG and NT were below the average. For all three years, among the grasses harvested in spring, NWG was above average, while AWG and CWR were below the average in yield. Among the grasses harvested in summer, NWG and MBG were above average, while JG was below or equal to the average. Among the grasses harvested in fall, HBG, MBG and NWG were above average, while AWG and JG were below the average.

In terms of relative quality score for all harvest seasons, in 2008, AWG and GNG were more than or equal to average, while NT was less than or equal to the average; in 2009, AWG, CWR, MBG and WWG were more than average, while NT and NWG were less than the average; in 2010, MBG was more than or equal to average, while NT and NWG were less than the average. For all three years, among the grasses harvested in spring, AWG, CWR and WWG were more than average, while NWG and NT were less than the average. Among the grasses harvested in summer, MBG was more than or equal to average, while NWG and NT were less than or equal to the average. Among the grasses harvested in fall, HBG, MBG and GNG were more than or equal to average, while NT was less than or equal to the average.

Taking into account the yield and relative quality score for the nine C3 grass species, MBG was higher than average in both yield and relative quality score in summer and fall over the three years. The HBG grass was higher than or close to average in both yield and relative quality score in fall over the three years. The NWG grass was nearly always more than average in yield and less than average in relative

Table 1
Covariance analysis (ANCOVA) of dry matter forage yield and quality indicators for the nine cool-season grasses harvested in spring, summer and fall over 2008–2010.

Effect	DMY (kg/ha)	ADF (%)	NDF (%)	CP (%)	OMD (%)	Ca (%)	P (%)
Covariate	< 0.001	0.0037	< 0.001	< 0.001	0.1073	0.5511	< 0.001
Year (Y)	< 0.001	< 0.001	< 0.001	0.0474	0.0014	< 0.001	< 0.001
Harvest (H)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.0483	< 0.001
Species (S)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.0028
Y × H	0.0382	< 0.001	0.0045	0.0059	0.1344	0.0091	< 0.001
H × S	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.1246
Y × S	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Y × H × S	0.0120	< 0.001	< 0.001	0.0915	0.0116	0.0143	< 0.001

Covariate: precipitation from previous October to current April; Year: 2008, 2009, 2010; Harvest: spring, summer, fall; Species: nine cool-season grass species; DMY = dry matter yield, OMD = organic matter digestibility, ADF = acid detergent fiber, NDF = neutral detergent fiber, CP = crude protein, Ca = calcium, P = phosphorus. $P > 0.10$ denotes not significant; $0.05 < P \le 0.10$ denotes marginally significant; $0.001 < P \le 0.05$ denotes significant; $P \le 0.001$ denotes highly significant.

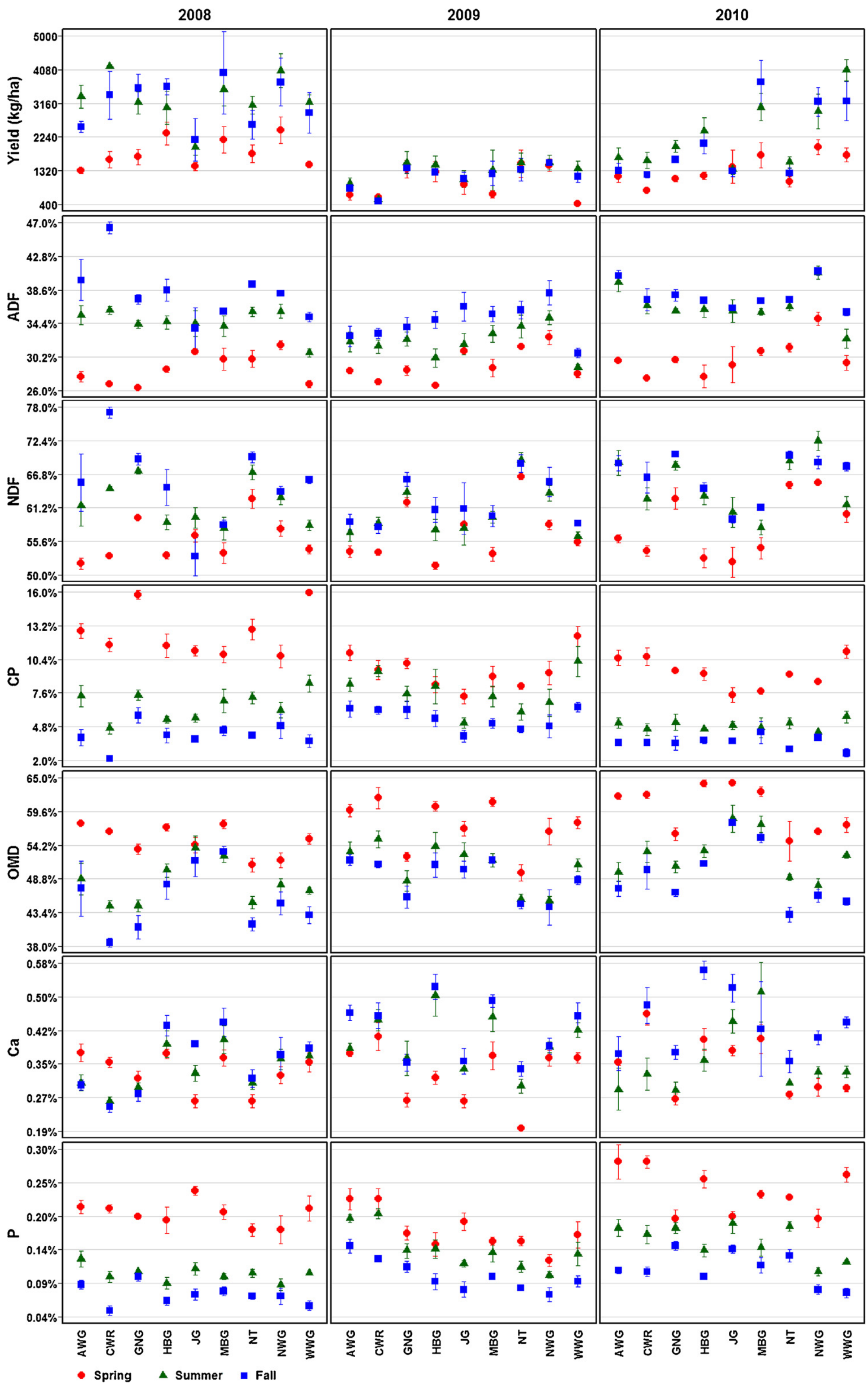

Fig. 2. The scatter diagrams with ± standard error (SE) bar among forage species based on Yield, ADF, NDF, CP, OMD, Ca and P for C3 grasses harvested in spring, summer, and fall during 2008–2010. Yield = dry matter yield, ADF = acid detergent fiber, NDF = neutral detergent fiber, OMD = organic matter digestibility, CP = crude protein, Ca = calcium, P = phosphorus, HBG = Hybrid bromegrass, MBG = Meadow bromegrass, AWG = Awned wheatgrass, CWR = Canada wild rye, WWG = Western wheatgrass, NT = Needle and thread grass, NWG = Northern wheatgrass, GNG = Green needlegrass, and JG = June grass.

quality score in any harvest season over the three-year period. The grasses CWR and AWG were more than average in relative quality score and less than average in yield in spring for the three years (Fig. 4).

4. Discussion

4.1. Covariance analysis

The main effects and their interactions of study years, harvest

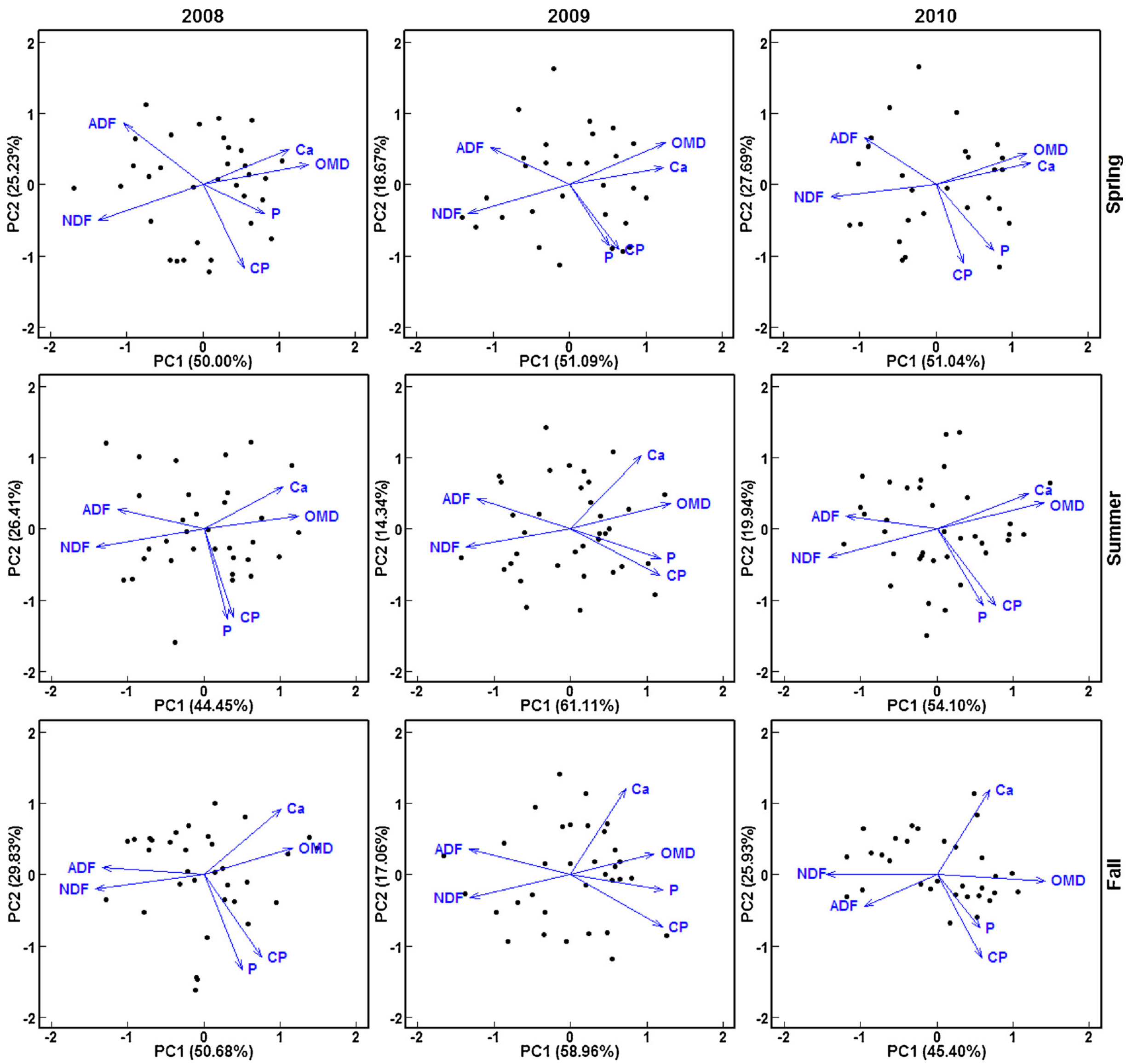

Fig. 3. The interrelationship patterns among forage quality indicators based on the PCA diagrams for the nine C3 grasses harvested in spring, summer, and fall during 2008–2010. The names of forage quality indicators are detailed in Fig. 2.

seasons and grass species on dry matter yield and forage quality indicators were investigated by using ANCOVA for the nine C3 grass species in the current study. The inter-annual variations of both dry matter forage yield and quality indicators were substantially significant (Table 1), which was primarily related to great differences in climate conditions among the study years (Daugėlienė and Žekonienė, 2009). For instance, there were uneven monthly precipitation distribution patterns (Fig. 1A) and inconsistent growing season precipitation between 2009 and the other two years (Fig. 1B). All variables were significantly affected by harvest seasons (Table 1), which were mostly associated with morphological and anatomical differences corresponding to forage growth stages at the time of harvest (Karn et al., 2006; Fulgueira et al., 2007). The inter-species variations of all variables were extremely significant (Table 1), which was primarily connected with their differences in biological and ecological characteristics (Karn et al., 2006; Zhao et al., 2008). Most, importantly, all the interactive effects of year, harvest season and species on dry matter yield and most of the quality indicators were significant in the study. These significant interactions indicated that it is necessary to make inter-species quality and yield evaluations year by year and season by season individually due to the large discrepancy and lack of homogeneity among years and among harvest seasons.

4.2. Interrelation pattern among forage quality indicators

Inter-annual, inter-seasonal and inter-species variations of dry matter yield showed large differences, with the exception of inter-seasonal variation in 2009. Moreover, most quality indicators exhibited expected inter-annual, inter-seasonal and inter-species variations over the three years. For example, forage quality tended to decline (e.g., ADF and NDF contents increased, and OMD and CP decreased) (Fig. 2) with grasses advancing in physiological maturity owing to increases of cell wall and fiber levels (Buxton, 1996). The rate and magnitude of decline in forage quality indicators were different from species to species due to genetic and morphological differences (Barre et al., 2006) as grasses matured. However, the interrelationships of forage quality indicators were relatively consistent and steady regardless of study year or harvest season (Fig. 3), although quality indicators and yields for C3 grasses varied among years and harvest seasons (Fig. 2). The PCA-based interrelationship diagrams reflecting the underlying data structures gave us an improved insight into understanding of interrelation patterns among quality indicators and determination of positive or negative

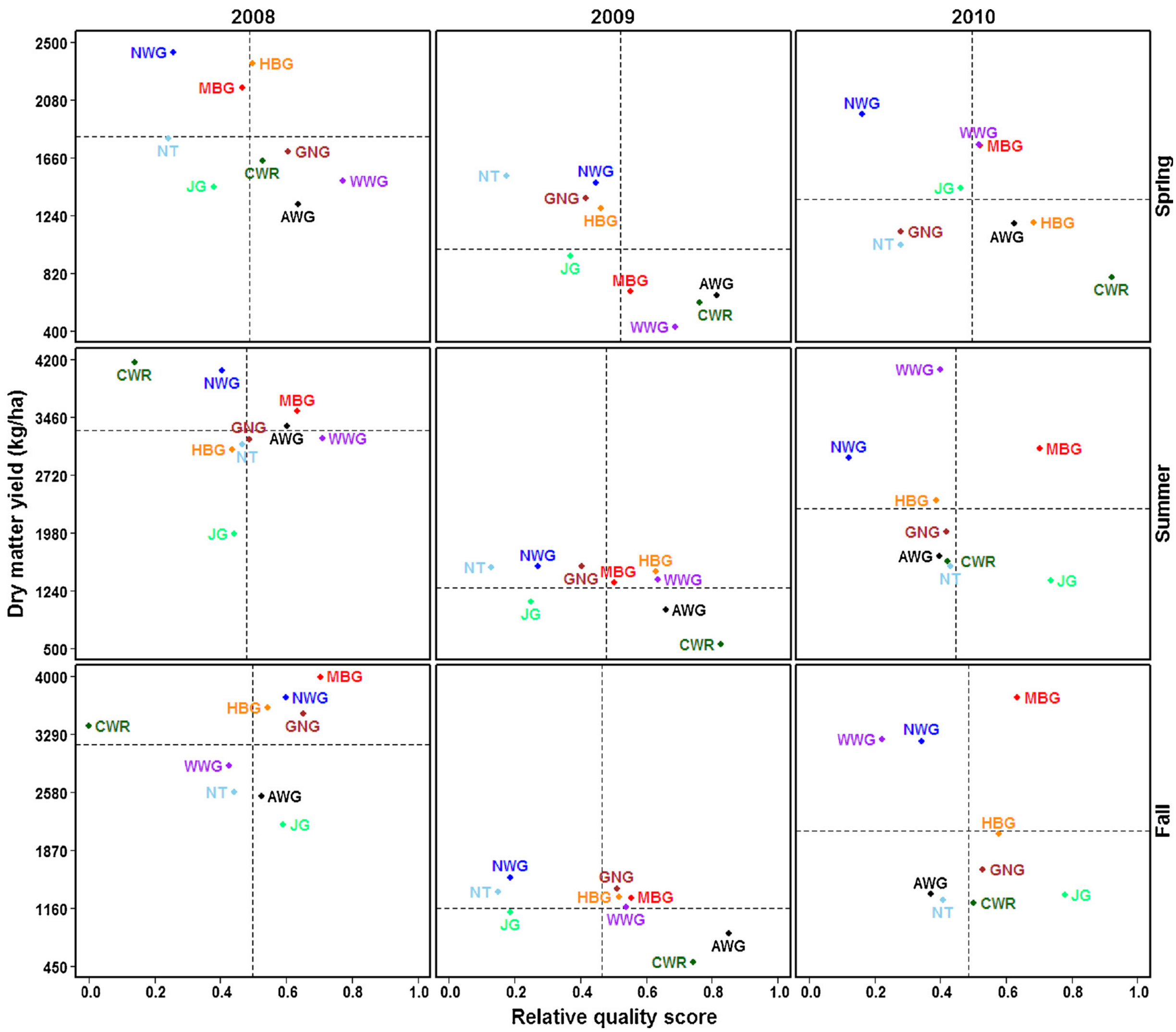

Fig. 4. The evaluation of forage yield and comprehensive quality based on TOPSIS with EW for the nine C3 grass species harvested in spring, summer, and fall during 2008–2010. The horizontal dashed line represents the average of forage yield and the vertical dashed line represents the average of relative quality scores. The names of forage quality indicators are detailed in Fig. 2.

attributes of indicators in the evaluation (Kenkel, 2006; Yeater et al., 2015). This insight was foundational for the next step in our comprehensive evaluation of forage quality.

Neutral detergent fiber in forage has a volume filling effect and can promote peristalsis of the digestive tract (Allen, 2000). However, high NDF content in forage can decrease intake and limit forage digestive effectiveness (Fulgueira et al., 2007). The higher the NDF content in the forage, the lower its quality (Ball et al., 2001); therefore NDF was treated as a negative quality indicator in the evaluation of forage quality. The ADF in forage was negatively correlated with digestibility and positively correlated with NDF (Fig. 3), which has also been confirmed by other studies (Norman et al., 2004; Zhao et al., 2008). Accordingly, ADF was also considered a negative quality indicator in the evaluation of forage quality.

Organic matter digestibility affects the absorption of nutrients for livestock. Forage of higher digestibility supplies more energy for livestock per unit of dry matter consumed than less digestible forage. Thus the grasses with increased digestibility are conducive to the growth of the livestock (Bruinenberg et al., 2002). In this study, OMD was consistently negatively correlated to ADF and NDF according to the PCA-based interrelationship diagrams for the nine C3 grasses harvested at three different seasons (Fig. 3), which was consistent with many other studies (Bumb et al., 2016). Thus, OMD was adopted as a positive indicator in the evaluation of forage quality.

Crude protein is necessary for the growth, development, lactation, reproduction and organ repair of livestock. High-protein forages are often high in energy and low-protein forages may limit animal performance (Ball et al., 2001). Based on the PCA diagrams, CP was positively correlated with OMD and negatively correlated with ADF and NDF (Fig. 3), which has also been reported by other studies (Zhao et al., 2008). Positive correlations between CP and OMD were revealed at all harvest seasons over the three years of the study, which agreed with other studies conducted on grass species (Bumb et al., 2016). However, the positive correlations between CP and OMD were less significant in spring than in summer and fall, which might be due to the facts that protein is mainly distributed in the young stems at the vegetative growth stage and the production of less stem material in summer and fall (Ferdinandez and Coulman, 2001; Karn et al., 2006).

The essential mineral elements must be supplied in the proper quantities and ratios to maintain animal function and growth. Generally, the mineral concentrations of grasses vary with harvest seasons, and often are below the requirements of livestock in one or more types of minerals for optimal performance and health (Grings et al., 1996). Low concentrations of essential minerals in forage may limit animal performance by impairing the ability of microorganisms to digest fiber and synthesize protein (Epstein, 1956). The main and most important minerals are Ca and P. The Ca:P ratio should be between 2:1 and 7:1 in the final ration (Gibb et al., 2008). In the present study, the range of Ca content was 0.16%–0.70%, the range of P content was 0.03%–0.37%, and the range of Ca:P ratio was 1.89:1–5.33:1, which means that the concentrations of Ca, P and their ratio were not excessive (Fig. 2). Although the growth stage affects the content of most minerals in forages, Ca showed a consistently negative correlation with ADF and NDF at each harvest season over the three-year period, which was in agreement with conclusion of McLean et al. (1969). Based on the PCA diagrams, Ca was positively correlated with OMD, which contrasted with the conclusion of McLean et al. (1969). However, Norman et al. (2004) reported that significant correlations between Ca and OMD, ADF, and NDF were not found. These inconsistent results may be explained by the findings of Gomide et al. (1969), who reported that the content of Ca in forage was less influenced by increasing maturity than other quality indicators and suggested that the association between Ca and OMD was complex and uncertain. Interestingly, the results suggested that the relationship between Ca and P generally changes from positive to negative as the harvest seasons advanced (Fig. 3). McLean et al. (1969) and Gao et al. (2016) found that Ca was negatively correlated with P, while Norman et al. (2004) found that there was no significant correlation between Ca and P. These phenomena were not surprising, because Ca content in forage was found to be less influenced by increasing maturity (Gomide et al., 1969), while P in plants decreased with plant maturity (Powell et al., 1978). Moreover, the changes in Ca and P were also closely associated with soil type and weather conditions (Karn et al., 2006). However, owing to Ca being consistently and negatively correlated with NDF and ADF (Fig. 3), Ca was still taken as a positive quality indicator in this study. As expected, P showed significant positive correlations with CP and significant negative correlations with ADF at each harvest season over the three years, which was in agreement with McLean et al. (1969). This finding might be due to the theory that P could promote the synthesis of protein (Epstein, 1956). Therefore, P was taken as a positive quality indicator in the evaluation of forage quality.

4.3. Evaluation and suggestion for both forage yield and comprehensive quality

It is necessary to find the positive or negative attributes of forage quality indicators by PCA method in order to determine interrelationships among the indicators in a comprehensive evaluation. On this basis, the evaluation of forage quality for the nine C3 grasses was conducted by using an integrated multi-index decision analysis method, namely, the PCA-based TOPSIS with EW. The integrated multi-index decision analysis method is a synthesis of three methods with complementary advantages that can reduce the random error and systematic error in the evaluation process and improve the credibility of the evaluation results (Guo, 2007).

In the present study, the magnitude of the difference in dry matter yield was particularly large between the dry year (2009) and wet years (2008 and 2010); dry matter yields in the wet years were about two or three times those of the dry year (Fig. 4). This suggested that for C3 grass species the impact of climatic conditions in the growing season on dry matter yield was enormous. The accumulation of dry matter was not only controlled by the growth rhythm of each grass species but was also limited by environmental factors. In fact, the growth process of grasses can be regarded as an integrated function of water and heat factors, but water was still the main environmental control factor of forage growth in semi-arid regions in most situations (Maffei, 2014). In the dry year (2009), there were marginal yield differences for grasses harvested at different harvest times (spring, summer and fall), which was mainly due to the continuous drought limiting the growth of grasses. However, in the wet years (2008 and 2010), dry matter yields of C3 grasses harvested in summer were far higher than in spring. In the summer of 2008, dry matter yields were the highest, primarily because rainfall was more abundant and more intensive in late spring (May) and early summer (June). Meanwhile, during this period, the grasses were just at the rapid elongation stage of shoots and tillers, which may in part account for the more pronounced differences in dry matter yield among the three harvest seasons in 2008 than both 2009 and 2010. This finding indicated that the effect of moisture at different time periods on the grasses growth was distinct at a given location. Under the suitable forage growing temperature, dry matter yields were closely related to seasonal distribution of precipitation (Robinson et al., 2013). Especially during the turning green period and the vigorous growing period of grasses, suitable hydro-thermal conditions could dramatically promote the growth of grasses (Daugėlienė and Žekonienė, 2009). In contrast, continuous drought or high temperature conditions at this time could restrict the growth of grasses. In short, sufficient moisture at the turning green stage and the vigorous growth stage was crucial to the growth of grasses under regular growing temperatures. However, regardless of the moisture conditions, forage quality for the majority of the nine C3 grass species harvested in spring was higher than in summer and fall. This was primarily because maturity stage at harvest was the most important factor affecting forage quality (Ball et al., 2001). Forage quality is not static but continually changes as grasses mature (Chaves et al., 2006). In fact, these forage quality differences between harvest seasons were mainly related to physiology, morphology and the leaf-to-stem-ratio (Gastal and Lemaire, 2015). For most perennial grasses, the germination and vegetative-leaf development stages occur in spring; the stem elongation and tiller elongation stages occur in summer; the reproductive-floral development and seed development and ripening stages occur in fall (Skinner and Moore, 2007). In spring, the plant matter mainly consists of leaves, tillers and young stem parts; in summer, the plant matter mainly includes large leaves, long tillers and long stems; in fall, the shoots of forage plants consist of leaves, stems, flowers and seeds if plant maturity has advanced beyond the vegetative stage. Moreover, at the early vegetative growth stages, very young stem tissue and leaves can be very similar in composition with high OMD and CP content, and low fiber content for most grass species (Ball et al., 2001). At the reproductive and seed ripening stages, the stems have much higher NDF and ADF levels and much lower OMD, CP and mineral contents than the leaves (Van Saun 2006). As grasses mature the forage quality nearly always gradually declines, although the quality of leaves decreases very little while the quality of stem decreases relatively quickly (Hoffman et al., 2003). In addition, the proportion of leaves in forage declines as the plant matures (Hoffman et al., 2003). Consequently, the leaf-to-stem ratio in the grasses can greatly impact overall forage quality.

In all three years, the rankings of forage relative quality scores were more discrete in spring and more centralized in summer and fall. This result suggested that almost all grasses have good quality in spring, and the degree of distinction for forage quality in spring was higher than in summer and fall. This finding was likely because the range of CP and P contents in the leaves and tillers varied more among the grass species in spring than in summer and fall (Fig. 2).

For all harvest seasons, in a dry year (2009), NT and NWG were above average in yield and below average in relative quality scores. Those two grass species have similar persistent ability to maintain green biomass throughout drought and cold conditions because they have extensive root systems with deep roots that provide moisture through times of drought (Redmann, 1976), which may explain why their yields were above the average. Their CP and OMD declined slowly in spring and then more rapidly through the summer and fall (Cogswell and Kamstra, 1976), which may account for their below-average relative quality scores. The grasses AWG and CWR were below average in yield and above average in the relative quality scores. This result may be related to their similar growing characteristics, including requiring high moisture conditions for their optimal growth, initiating growth later in the spring and having moderate tolerance to drought and cold stresses (Kusler, 2009). The JG grass was below average in both yield and relative quality scores, which may be due to its shorter plant height despite it being tolerant to drought, cold and heat stresses (Kusler, 2009). In the wet years (2008 and 2010), MBG was above average in both yield and relative quality scores, likely because MBG was well adapted to the cool and moist growing conditions of the western Canadian prairie region and because it had better frost tolerance (Kusler, 2009).

During the study's three years, in spring, NWG had above average in yield and below average in relative quality scores; AWG and CWR had below average in yield and above average in relative quality scores, which was basically consistent with the conclusion of Kusler (2009) that CWR was best grazed in the spring before the culms elongate. In summer and fall, MBG was above average in both yield and relative quality. This finding was likely because it had great re-growth potential after defoliation as re-growth was initiated in existing tiller bases and not from the crown (Kusler, 2009).

In all study years and harvest seasons, NWG was consistently above average yields, which was consistent with the conclusion of Pahl and Smreciu (1999) that recognized NWG as one of the most productive grasses on the Northern Great Plains. The AWG grass had consistently below average yields, which may be because it is less leafy than other C3 grasses (Pahl and Smreciu, 1999). The NT grass was consistently below average in relative quality scores, which may be linked to its narrow leaves, rough stems, hard seeds and slender awns. Thompson et al. (2003) stated that NT grass is best moderately grazed in spring or early summer while it is still palatable. The MBG grass was consistently above average in relative quality scores, partly because it was well adapted to Canadian growing conditions, produced a higher canopy, and became dormant later than other grasses.

Simultaneously, considering both quality and yield for the nine C3 grass species, the MBG performed above average in summer and fall over the three years. The result was consistent with the conclusion that MBG was palatable and could be utilized as fall pasture as it grew well under cooler temperatures and held its forage quality later into the grazing season compared with many other cool-season grasses (Ferdinandez and Coulman, 2001; Thompson et al., 2003). This also agreed with Kusler's (2009) conclusion that MBG was one of the most widely recognized grasses for use under intensive rotational grazing because of its high palatability and excellent recovery. The HBG, similar to MBG, was higher than or close to average in both yield and relative quality in summer and fall. Coulman (2004) reported a similar result that HBG produced equal pasture yield and carrying capacity as MBG. This was not unexpected since HBG was developed by crossing smooth brome grass and MBG, and it shared some characteristics of both the two parental species (Thompson et al., 2003; Coulman, 2004).

5. Conclusions

The present study demonstrated that dry matter forage yield and quality indicators of the nine C3 grass species varied with the study years, harvest seasons and grass species in the semi-arid environment. Surprisingly, the interrelation patterns among quality indicators did not change with years or harvest seasons, even though the climate conditions were different each year. However, the rankings of most grasses in yield and comprehensive quality changed year by year and season by season, with the exception that the high yield of NWG, the low yield of AWG and the low quality of NT were almost always evident, regardless of season. MBG almost always produced high quality and high yields in summer and fall. Through the successful use of the integrated multi-index decision analysis method, i.e., PCA-based TOPSIS with EW, it was feasible to identify which C3 grass species can produce optimal forage quality and biomass under changing multivariate conditions. These findings will assist plant breeders in determining what forage species could achieve optimal performance in forage quality and production and/or what complementary species should be considered in mixed forage experiments.

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Appendix A

Eq. A. Formulas and procedures of comprehensive evaluation based on TOPSIS with EW.

Step 1. Constructing the normalized evaluating matrix.

$$Y = (y_{ij})_{n\times m} = (x_{ij}/\sum_{i=1}^{n} x_{ij})_{n\times m} \quad i = 1,2,\ \ldots, n;\ j = 1,2,\ \ldots, m. \tag{1}$$

Where, x_{ij} is actual measured value of evaluating indicator j in sample i.

Step 2. Calculating the entropy weight (EW) of each evaluating indicator.

$$w_j = \frac{1 + (1/\ln\ n)\sum_{j=1}^{m}[(y_{ij}/\sum_{i=1}^{n} y_{ij})\cdot\ln(y_{ij}/\sum_{i=1}^{n} y_{ij})]}{\sum_{j=1}^{m}\left\{1 + (1/\ln\ n)\sum_{j=1}^{m}[(y_{ij}/\sum_{i=1}^{n} y_{ij})\cdot\ln(y_{ij}/\sum_{i=1}^{n} y_{ij})]\right\}} \quad i = 1,2,\ \ldots, n;\ j = 1,2,\ \ldots, m. \tag{2}$$

Step 3. Constructing the normalized evaluation matrix with EW.

$$Z = (z_{ij})_{n\times m} = (w_i\cdot y_{ij})_{n\times m} \quad i = 1,2,\ \ldots, n;\ j = 1,2,\ \ldots, m. \tag{3}$$

Step 4. Determining the positive and negative ideal samples.

$$z_j^{+} = \begin{cases} \max\limits_{1\le i\le n}\ z_{ij} & the-bigger-the-better\ \ indicator \\ \min\limits_{1\le i\le n}\ z_{ij} & the-smaller-the-better\ \ indicator \end{cases} \quad i = 1,2,\ \ldots, n;\ j = 1,2,\ \ldots, m. \tag{4}$$

$$z_j^- = \begin{cases} \min\limits_{1 \le i \le n} z_{ij} \ \ the - bigger - the - better \ \ indicator \\ \max\limits_{1 \le i \le n} z_{ij} \ \ the - smaller - the - better \ \ indicator \end{cases} \quad i = 1,2, \ ..., n; j = 1,2, \ ..., m. \tag{5}$$

Step 5. Calculating the distance between evaluating sample with positive and negative ideal samples.

$$D_i^+ = \sqrt{\sum_{i=1}^{m} (z_{ij} - z_j^+)^2} \quad i = 1,2, \ ..., n; j = 1,2, \ ..., m. \tag{6}$$

$$D_i^- = \sqrt{\sum_{i=1}^{m} (z_{ij} - z_j^-)^2} \quad i = 1,2, \ ..., n; j = 1,2, \ ..., m. \tag{7}$$

Step 6. Calculating the comprehensive scores of evaluating sample in all evaluating indicators.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad i = 1,2, \ ..., n. \tag{8}$$

Eq. B. The degree of discrimination is an important index to evaluate the stability, sensitivity and reliability of an evaluation method. The high degree of discrimination means that the distance between two adjacent points of the evaluation result is larger and the probability of ranking misclassification is smaller. In addition, the high degree of discrimination also indicates that the sensitivity of the evaluation method is low and the ranking is more stable and reliable.

The formula for discrimination degree:

$$D = \frac{\sum_{i=1}^{m-1} \sqrt{(V_{i+1}^* - V_i^*)^2 + (N_{i+1} - N_i)^2}}{\sqrt{(V_m^* - V_1^*)^2 + (N_m - N_1)^2}} = \frac{\sum_{i=1}^{m-1} \sqrt{(V_{i+1}^* - V_i^*)^2 + 1}}{\sqrt{2m^2 - 2m - 1}} \tag{1}$$

Where, m is the number of evaluation objects; $V_i^* = m \times (1 - \frac{|V_1 - V_i|}{V_1 - V_m})(1 \le i \le m)$ is the standardized score of the ith object; V_i and $N_i (1 \le i \le m)$ are the decreasing listed scores and corresponding increasing listed rankings of the ith object. If $1 \le D \le 1.5$, then the ranking is reasonable. If $D > 1.5$, then the ranking is stable and reliable.

Table A1
Entropy weights (EWs) of six forage quality indicators based on positive or negative evaluating indicators from PCA.

Year	Season	OMD	ADF	NDF	CP	Ca	P
2008	Spring	0.1682	0.1677	0.1678	0.164	0.1652	0.1670
	Summer	0.1682	0.1687	0.1684	0.1628	0.1651	0.1668
	Fall	0.1700	0.1706	0.1702	0.1610	0.1647	0.1635
2009	Spring	0.1696	0.1696	0.1692	0.1658	0.1615	0.1643
	Summer	0.1698	0.1701	0.1699	0.1626	0.1657	0.1619
	Fall	0.1696	0.1696	0.1697	0.1655	0.1653	0.1603
2010	Spring	0.1691	0.1687	0.1683	0.1664	0.1624	0.1652
	Summer	0.1688	0.1689	0.1686	0.1685	0.1613	0.1639
	Fall	0.1684	0.1698	0.1695	0.1664	0.1652	0.1608

ADF = acid detergent fiber, NDF = neutral detergent fiber, OMD = organic matter digestibility, CP = crude protein, Ca = calcium, and P = phosphorus.

Table A2
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **spring** of 2008.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1165	0.1223	0.1247	0.1408	0.1261	0.1307	1	–
NIGS	0.1033	0.1018	0.1033	0.0944	0.0880	0.0974	0	–
AWG	0.1165	0.1073	0.1033	0.1127	0.1261	0.1168	0.6363	2
CWR	0.1140	0.1037	0.1057	0.1027	0.1184	0.1154	0.5292	4
GNG	0.1083	0.1018	0.1184	0.1394	0.1058	0.1085	0.6064	3
HBG	0.1154	0.1106	0.1059	0.1021	0.1252	0.1057	0.4991	5
JG	0.1096	0.1193	0.1125	0.0983	0.0880	0.1307	0.3792	7
MBG	0.1164	0.1157	0.1067	0.0955	0.1218	0.1127	0.4656	6
NT	0.1033	0.1157	0.1247	0.1141	0.0880	0.0974	0.2420	9
NWG	0.1048	0.1223	0.1149	0.0944	0.1083	0.0974	0.2573	8
WWG	0.1117	0.1036	0.1079	0.1408	0.1184	0.1154	0.7740	1

ADF = acid detergent fiber, NDF = neutral detergent fiber, OMD = organic matter digestibility, CP = crude protein, Ca = calcium, P = phosphorus; CRQS = comprehensive relative quality scores based on TOPSIS with EW; NIGS = positive ideal grass species; PIGS = negative ideal grass species; HBG = Hybrid bromegrass, MBG = Meadow bromegrass, AWG = Awned wheatgrass, CWR = Canada wild rye, WWG = Western wheatgrass, NT = Needle and thread grass, NWG = Northern wheatgrass, GNG = Green needlegrass, and JG = June grass.

Table A3
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **summer** of 2008.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1239	0.1158	0.1206	0.1417	0.1342	0.1358	1	–
NIGS	0.1024	0.0987	0.1036	0.0791	0.0867	0.0940	0	–
AWG	0.1125	0.1138	0.1105	0.1243	0.1008	0.1358	0.6020	3
CWR	0.1024	0.1158	0.1155	0.0791	0.0867	0.1070	0.1388	9
GNG	0.1026	0.1103	0.1206	0.1259	0.0975	0.1149	0.4888	4
HBG	0.1156	0.1110	0.1054	0.0914	0.1308	0.0966	0.4366	7
JG	0.1239	0.1104	0.1068	0.0933	0.1083	0.1201	0.4418	6
MBG	0.1209	0.1094	0.1036	0.1177	0.1342	0.1070	0.6333	2
NT	0.1038	0.1152	0.1203	0.1222	0.1008	0.1123	0.4663	5
NWG	0.1102	0.1154	0.1128	0.1044	0.1192	0.0940	0.4037	8
WWG	0.1081	0.0987	0.1045	0.1417	0.1217	0.1123	0.7108	1

Note: The names of all abbreviations are detailed in Table B.

Table A4
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **fall** of 2008.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1298	0.1345	0.1312	0.1562	0.1403	0.1541	1	–
NIGS	0.0944	0.0981	0.0905	0.059	0.0784	0.0752	0	–
AWG	0.1155	0.1156	0.1114	0.1061	0.0943	0.1353	0.5257	6
CWR	0.0944	0.1345	0.1312	0.0590	0.0784	0.0752	0.0000	9
GNG	0.1004	0.1087	0.1180	0.1562	0.088	0.1541	0.6507	2
HBG	0.1172	0.1119	0.1100	0.1116	0.1379	0.0977	0.5441	5
JG	0.1264	0.0981	0.0905	0.1027	0.1244	0.1128	0.5912	4
MBG	0.1298	0.1043	0.0995	0.1226	0.1403	0.1203	0.7041	1
NT	0.1015	0.114	0.1186	0.1108	0.0990	0.1090	0.4411	7
NWG	0.1097	0.1107	0.1087	0.1324	0.1165	0.1090	0.5987	3
WWG	0.1051	0.1023	0.1122	0.0985	0.1212	0.0865	0.4267	8

Note: The names of all abbreviations are detailed in Table B.

Table A5
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **spring** of 2009.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1196	0.1242	0.1291	0.1448	0.1414	0.1422	1	–
NIGS	0.0965	0.1015	0.1005	0.0863	0.0678	0.0815	0	–
AWG	0.1157	0.1083	0.1050	0.1288	0.1276	0.1422	0.8142	1
CWR	0.1196	0.1031	0.1048	0.1123	0.1414	0.1422	0.7611	2
GNG	0.1015	0.1086	0.1210	0.1184	0.0905	0.1086	0.4167	7
HBG	0.1170	0.1015	0.1005	0.0977	0.1087	0.0974	0.4612	5
JG	0.1101	0.1177	0.1137	0.0863	0.0897	0.1198	0.3685	8
MBG	0.1183	0.1097	0.1042	0.1059	0.1259	0.1006	0.5505	4
NT	0.0965	0.1197	0.1291	0.0963	0.0678	0.1006	0.1734	9
NWG	0.1092	0.1242	0.1137	0.1095	0.1242	0.0815	0.4477	6
WWG	0.1120	0.1071	0.1080	0.1448	0.1242	0.1070	0.6893	3

Note: The names of all abbreviations are detailed in Table B.

Table A6
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **summer** of 2009.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1207	0.1214	0.1272	0.1482	0.1407	0.1536	1	–
NIGS	0.0991	0.1000	0.1039	0.0744	0.0822	0.0806	0	–
AWG	0.1163	0.1110	0.1049	0.1206	0.1065	0.1478	0.6600	2
CWR	0.1207	0.1091	0.1078	0.1364	0.1247	0.1536	0.8282	1
GNG	0.1060	0.1122	0.1174	0.1095	0.1003	0.1094	0.4045	6
HBG	0.1181	0.1040	0.1058	0.1186	0.1407	0.1113	0.6303	4
JG	0.1152	0.1100	0.1063	0.0744	0.0933	0.0940	0.2474	8
MBG	0.1133	0.1145	0.1097	0.1061	0.1267	0.1075	0.5008	5
NT	0.0997	0.1178	0.1272	0.0875	0.0822	0.0902	0.1291	9
NWG	0.0991	0.1214	0.1170	0.0988	0.1072	0.0806	0.2697	7
WWG	0.1116	0.1000	0.1039	0.1482	0.1184	0.1056	0.6352	3

Note: The names of all abbreviations are detailed in Table B.

Table A7
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **fall** of 2009.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1178	0.1225	0.1230	0.1308	0.1373	0.1609	1	–
NIGS	0.1008	0.0985	0.1041	0.0820	0.0876	0.0804	0	–
AWG	0.1178	0.1053	0.1056	0.1283	0.1216	0.1609	0.8526	1
CWR	0.1163	0.1064	0.1041	0.1257	0.1197	0.1394	0.7447	2
GNG	0.1044	0.1089	0.1183	0.1263	0.0916	0.1260	0.5119	5
HBG	0.1162	0.1118	0.1092	0.1114	0.1373	0.1019	0.5171	4
JG	0.1144	0.1170	0.1096	0.0820	0.0922	0.0885	0.1863	8
MBG	0.1177	0.1141	0.1074	0.1035	0.1288	0.1099	0.5048	6
NT	0.1018	0.1157	0.1230	0.0933	0.0876	0.0912	0.1490	9
NWG	0.1008	0.1225	0.1175	0.0987	0.1014	0.0804	0.1879	7
WWG	0.1106	0.0985	0.1052	0.1308	0.1197	0.1019	0.5400	3

Note: The names of all abbreviations are detailed in Table B.

Table A8
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **spring** of 2010.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1188	0.1300	0.1251	0.1322	0.1482	0.1322	1	–
NIGS	0.1016	0.1014	0.0998	0.0889	0.0849	0.0909	0	–
AWG	0.1148	0.1105	0.1073	0.1257	0.1122	0.1322	0.6436	3
CWR	0.1153	0.1026	0.1033	0.1265	0.1482	0.1322	0.9225	1
GNG	0.1038	0.1110	0.1200	0.1129	0.0849	0.0909	0.2798	7
HBG	0.1187	0.1032	0.1010	0.1098	0.1290	0.1196	0.6837	2
JG	0.1188	0.1014	0.0998	0.0889	0.1210	0.0921	0.4611	6
MBG	0.1163	0.115	0.1042	0.0926	0.1298	0.1086	0.5204	4
NT	0.1016	0.1168	0.1243	0.1094	0.0881	0.1062	0.2772	8
NWG	0.1045	0.1300	0.1251	0.1021	0.0937	0.0909	0.1601	9
WWG	0.1063	0.1095	0.1149	0.1322	0.0929	0.1275	0.5164	5

Note: The names of all abbreviations are detailed in Table B.

Table A9
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **summer** of 2010.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1237	0.1235	0.1239	0.1275	0.1619	0.1310	1	–
NIGS	0.1011	0.0986	0.0992	0.0985	0.0900	0.0779	0	–
AWG	0.1056	0.1198	0.1176	0.1155	0.0908	0.1257	0.3961	7
CWR	0.1124	0.1110	0.1073	0.1038	0.1019	0.1186	0.4215	4
GNG	0.1074	0.1091	0.1168	0.1173	0.0900	0.1257	0.4177	5
HBG	0.1128	0.1097	0.1081	0.1042	0.1122	0.1009	0.3857	8
JG	0.1237	0.1090	0.1035	0.1112	0.1406	0.1310	0.7361	1
MBG	0.1218	0.1086	0.0992	0.1066	0.1619	0.1044	0.7009	2
NT	0.1039	0.1107	0.1181	0.1155	0.0956	0.1274	0.4293	3
NWG	0.1011	0.1235	0.1239	0.0985	0.1035	0.0779	0.1222	9
WWG	0.1112	0.0986	0.1056	0.1275	0.1035	0.0885	0.3995	6

Note: The names of all abbreviations are detailed in Table B.

Table A10
Normalized value of forage quality indicators, comprehensive relative quality scores and ranks based on TOPSIS with EW for C3 grasses harvested in **fall** of 2010.

Species	ADF	NDF	CP	OMD	Ca	P	CRQS	Ranks
PIGS	0.1304	0.1202	0.1175	0.1380	0.1429	0.1449	1	–
NIGS	0.0972	0.1052	0.0994	0.0837	0.0894	0.0749	0	–
AWG	0.1067	0.1185	0.1150	0.1103	0.0939	0.1087	0.3719	7
CWR	0.1135	0.1097	0.1110	0.1098	0.1224	0.1063	0.5019	5
GNG	0.1053	0.1114	0.1175	0.1088	0.0947	0.1449	0.5295	4
HBG	0.1158	0.1094	0.1080	0.1168	0.1429	0.0990	0.5771	3
JG	0.1304	0.1066	0.0994	0.1148	0.1326	0.1401	0.7791	1
MBG	0.1249	0.1093	0.1027	0.1380	0.1085	0.1159	0.6345	2
NT	0.0972	0.1098	0.1171	0.0940	0.0894	0.1304	0.4073	6
NWG	0.1041	0.1202	0.1152	0.1237	0.1034	0.0797	0.3436	8
WWG	0.1020	0.1052	0.1141	0.0837	0.1123	0.0749	0.2240	9

Note: The names of all abbreviations are detailed in Table B.

Table A11
The discrimination degree of scores and rankings for forage comprehensive quality evaluation in terms of PCA-based TOPSIS with EW for the nine C3 grasses harvested in spring, summer and fall (2008–2010).

2008			2009			2010		
Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
1.9704	2.3059	2.3378	2.0622	2.6102	2.0723	2.4307	1.8762	1.5137

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