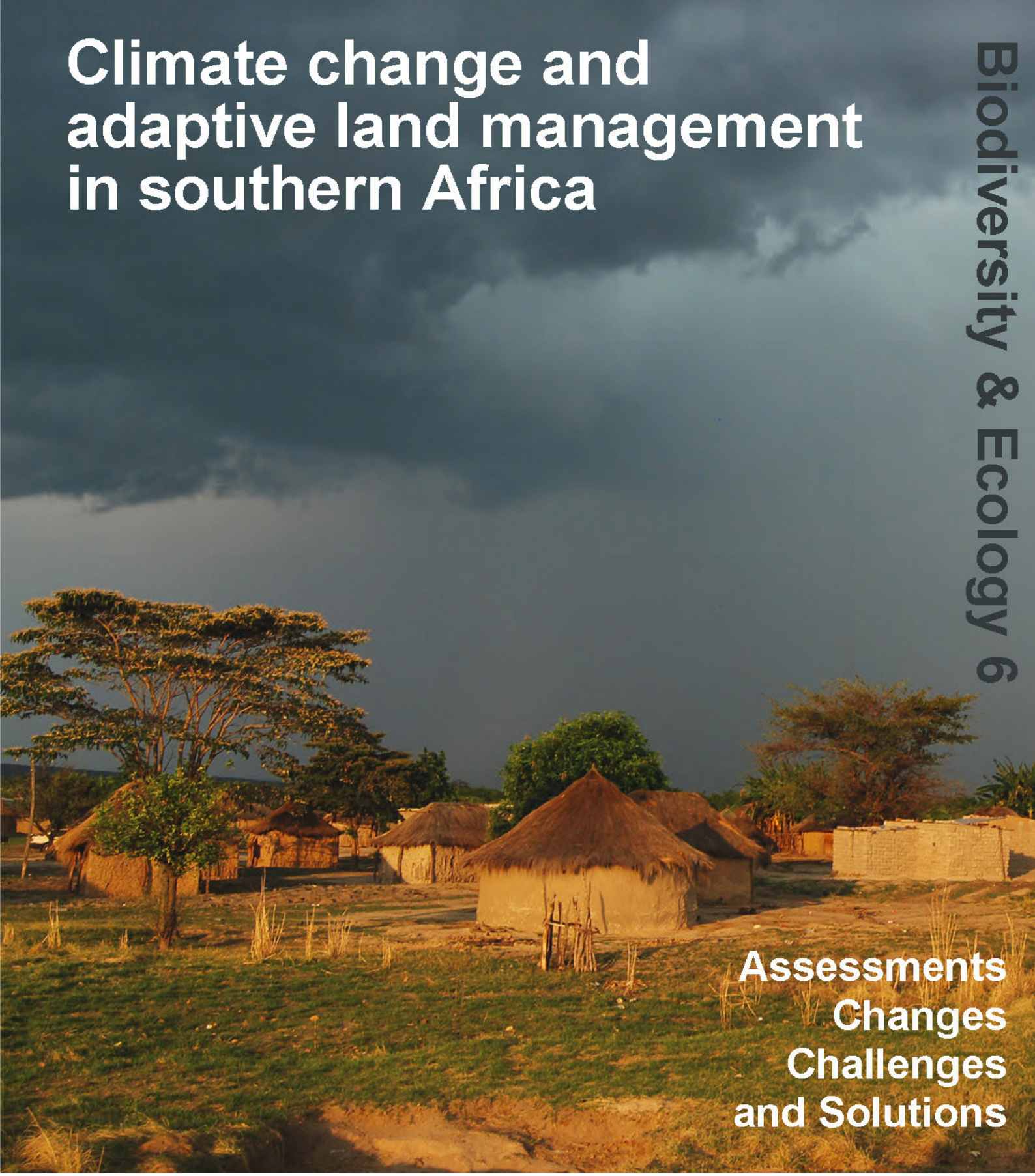
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



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Quality of wild herbaceous legumes and its role in livestock nutrition

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Abstract: Climate change in southern Africa is predicted to be severe, and animal agriculture will suffer the most. However, there exist wild legumes that have survived under harsh environmental conditions and contribute to a varied diet for the grazing ungulates. This study tested the chemical composition of four wild herbaceous legumes each from Tswapong and Ngamiland districts in Botswana (*Chamaecrista abscus, Chamaecrista rotundifolia, Crotalaria sphaerocarpa, Tephrosia lupinifolia, Tephrosia purpurea, Indigofera* sp., *Zornia glochidiata*.). These plant species were previously found to fix nitrogen in the soil by the SASSCAL research Task 316, and the plant selection was also guided by informed focus discussions with farmers. For Tswapong the results show that *C. rotundifolia* and *T. purpurea* had the highest level of crude protein (CP) while *Z. glochidiata* had the least CP. In vitro gas production showed high gas yield for *Z. glochidiata*, and a small volume of gas was produced by *T. lupinifolia*. Condensed tannins (CT) were higher for *Z. glochidiata* and *C. rotundifolia* but lower for *T. purpurea and T. lupinifolia*. CT were at similar concentration for *C. rotundifolia* and *Z. glochidiata*. No relationship was detected between condensed tannins and crude protein. With regard to samples from Ngamiland, there was no differences among plant species for acid detergent fibre (ADF), whereas other parameters measured were significantly different among the legume plants. *Indigofera sp*. had the highest CP, while *Crotalaria sphaerocarpa* had the lowest. In general, levels of crude protein were different among the legumes investigated but overall were higher than in natural grass, indicating their importance in providing protein to grazing ungulates in rangelands. Their high protein content also suggests the plants' potential as protein supplements if domesticated as fodder crops. However, palatability, toxicity, and intake should be tested in future studies before any recommendations are made.

Resumo: Prevê-se que as alterações climáticas no Sul de África sejam severas, e a agricultura animal será a que irá sofrer mais. Porém, existem leguminosas silvestres que sobreviveram sob condições ambientais severas e contribuem para uma dieta variada dos ungulados de pastagem. Este estudo testou a composição química de quatro leguminosas herbáceas silvestres, cada uma dos distritos de Tswapong e Ngamiland no Botswana (*Chamaecrista abscus, Chamaecrista rotundifolia, Crotalaria sphaerocarpa, Tephrosia lupinifolia, Tephrosia purpurea, Indigofera* sp., *Zornia glochidiata*). Foi previamente descoberto pela equipa de trabalho 316 do SASSCAL que estas espécies de plantas fixam azoto no solo, tendo a selecção de plantas sido também guiada por discussões de foco informado com agricultores. Para Tswapong, os resultados mostram que *C. rotundifolia* e *T. purpurea* tiveram os níveis mais elevados de proteína bruta (CP), enquanto que *Z. glochidiata* teve a menor quantidade de CP. In vitro, a produção de gás mostrou um elevado rendimento pela Z. *glochidiata*, enquanto que um pequeno volume de gás foi produzido pela *T. lupinifolia*. Taninos condensados (CT) foram mais elevados na *Z. glochidiata* e *C. rotundifolia*, mas menos elevados na *T. purpurea* e *T. lupinifolia*. Os CT tinham concentrações semelhantes na *C. rotundifolia* e *Z. glochidiata* Nenhuma relação foi detectada entre os taninos condensados e a proteína bruta. Em relação às amostras de Ngamiland, não houve diferenças entre as espécies de plantas em relação à fibra detergente ácida (ADF), enquanto que outros parâmetros medidos foram significativamente diferentes entre as plantas leguminosas. *Indigofera sp*. teve a maior CP, enquanto que *Crotalaria sphaerocarpa* teve a menor. No geral, os níveis de proteína bruta foram diferentes entre as espécies de leguminosas investigadas, mas globalmente foram maiores que em gramíneas naturais, indicando a sua importância no fornecimento de proteína aos ungulados em pastagens. O seu elevado conteúdo de proteína sugere também o potencial das plantas como suplemento de proteína se domesticadas como culturas forrageiras. No entanto, a palatabilidade, toxicidade e ingestão deverão ser testadas em estudos futuros antes de serem feitas quaisqueres recomendações.

Introduction

With the advent of climate change and prolonged dry periods, grazing ungulates will face challenges in terms of meeting their nutrient requirements for maintenance, growth, reproduction, and immunity. Prior to the arrival of these challenges and constraints, both livestock and wildlife have survived in harsh arid and semi-arid environments thanks to their unique utilization of rangeland resources. Their adaptation to fluctuations in forage quality, especially nitrogen levels, has resulted in the evolution of a nitrogen conservation mechanism, especially in ruminants, through the recycling of scarce nitrogen back into their digestive systems. This has prepared these animals to be fit for these particular environments (Wilson, 2009). Even though the animals evolved in rangelands with supposedly low nutritive value, in reality these rangelands do contain some plant species with high nutritive value. Nevertheless, the plants also contain anti-nutritive attributes from having adapted to the grazing by herbivores. These plant species such as herbaceous legumes have higher nutritive value compared to grasses. In the wild, these herbaceous and shrubby legumes (Fig. 1) contribute to dietary diversity and supply needed nutrients to meet requirements for the maintenance, growth, reproduction, and immune function of grazing animals in rangelands. Some species grow spontaneously in ploughed fields, thus fertilising the soil through nitrogen fixation and as green fertiliser when ploughed in (Bernard et al., 2017; Obopile et al., 2018). In most cases, the importance of such plant species is not appreciated until there is drought or a long dry period. With increasing feed shortages in the rangelands resulting from the effects of climate change, therefore, herbaceous legumes will become even more important. To formulate better strategies for their utilisation, however, wild legumes need to be characterised and suitable ones identified.

Utilisation of shrubby wild legumes has been recognised in improving ruminant production elsewhere; for example, one legume in Indonesia, *Indigofera arrecta,* was identified as a potential fodder plant. It was found to produce as much as 28 tons of dry matter per hectare per year with a high protein content of 27–29% and dry matter digestibility ranging between 67% and 81% (Abdullah & Kumalarasi, 2011). However, wild legumes have also been observed to contain condensed tannins (CT). Compounds such as condensed tannins, alkaloids, and saponins, commonly called secondary metabolites, act as natural defence of trees and plants against herbivores and pests (Stolter, 2018). In terms of the nutrition of grazing animals, CT can have both beneficial and detrimental effects on animals' health and digestion, depending on the concentration and structure of condensed tannins. At lower concentrations of less than 5 g/kg, condensed tannins bind with proteins, reducing their degradation in the rumen (Hoste et al., 2012). After the tannin-protein complex has dissociated in the acidic environment of the abomasum (Naumann et al., 2014), however, protein becomes available to the small intestine (Tedeschi et al., 2014). This will result in an increase in the supply and absorption of essential amino acids (Waghorn et al., 1987), benefiting growth, milk production, and immune function. On the other hand, high CT concentrations in the diets of grazing ungulates compromise palatability, voluntary intake, digestibility, and nitrogen retention (Silanikove et al., 2001). Other research (Jensen, 2012; Lamy et al., 2011) has reported that grazing plants containing tannins modulate grazing behaviour, and the motive for grazing plants with high secondary compounds may be to achieve physiological homeostasis, which could be viewed as self-medication (Stolter et al., 2018; Villalba & Landau, 2012). Therefore, to understand the contributions of different wild herbaceous legumes to the nutrition of grazing livestock in rangelands and arable lands, their nutritive value must be determined. This process should also involve the quantification of secondary metabolites. This will enable formulation of effective and sustainable as well as ecologically and environmentally sound utilisation of rangelands (Lamy et al., 2011) and the use of legumes as protein supplements or their adoption as fodder crops. Some plant species studied here were found to fix nitrogen (Bernard et al., 2017), others grow in arable fields, and others were observed to have been browsed; their selection was also partly guided by informed focus discussions with farmers in the studied areas (results not shown). Therefore, this study was carried out to determine the nutritive value and to quantify the amount of condensed tannins in wild herbaceous legumes in two ecological regions of Botswana. This study is part of the larger study sponsored by SASSCAL, and the plants studied are among a consortium of herbaceous plants investigated by Task 316 (Making use of the wild legume resource to improve arable and livestock farming in Botswana).

Materials and methods

Sample collection and analysis

Three to four plants per species were obtained by random sampling from rangelands in two districts of Ngamiland and Tswapong in Botswana except *Chamaecrista* spp., which were obtained from arable lands. Sites of sampling were previously described by Bernard et al. (2017). The sampled species were *Chamaecrista rotundifolia*, *Tephrosia purpurea*, *Tephrosia lupinifolia,* and *Zornia glochidiata* in Tswapong district and *Chamaecrista abscus, Indigofera* sp., *Crotalaria sphaerocarpa,* and *Tephrosia* sp. in Ngamiland, sampled during the flowering stage. The genus *Tephrosia* belongs to the Leguminosae family, and according to Chen et al. (2014) many of the species have important traditional uses in agriculture because they possess the bioactivity of phytoalexins. *Chamaecrista rotundifolia* was previously described by Tarawali (1995) as having potential for mixed legume pastures and having good dry matter productivity, excellent seed production, and persistence. According to Hassen et al. (2018), *Indigofera* sp. display excellent adaptation to a range of environments and possess diverse morphological and agronomic attributes significant to their use as forage and cover crops. Identification was done in the field and at the Botswana University of Agriculture and Natural Resources (BUAN) Herbarium and

Figure 1: Images showing a few of the herbaceous plants used in this study: (a) *Chamaecrista abscus*, (b) *Zornia glochidiata*, (c) *Crotalaria sphaerocarpa*. Photos: O.R. Madibela.

the Botswana National Herbarium and Botanic Gardens in Gaborone (Bernard et al., 2017). The plants were selected as guided by informed group discussions with farmers from the two regions (data not shown) and also by the abundance of certain plants in the localities. Samples were cut at 5 cm above ground level and transported to the laboratory, where samples from the same plant were pooled together before drying in an oven set at 60˚C for 48 hours. After drying the samples were milled to pass through a 3 mm sieve.

Chemical Analysis

Dry matter, ash, acid detergent fibre (ADF), neutral detergent fibre (NDF), and crude protein were determined according to standard methods of AOAC (1996). For detailed description of these parameters, refer to the info box "What Is Quality for a Ruminant?" by Stolter (2018). *Lablab purpureus* is a common fodder crop among small-scale livestock farmers in southern Africa and therefore was used as a control. However, this was done only for samples from Tswapong.

Table 1: Differences in chemical composition (g/kg) and in vitro gas production (ml/0.5 g) of different wild legumes species from Tswapong. DM = dry matter; CP = crude protein; NDF = neutral fibre; CT = condensed tannins; SEM = standard error of mean

Plants	DM	Ash	CP	NDF	CT	Gas
Chamaecrista rotundifolia	974	188	324	481	2.53	35
Tephrosia purpurea	969	246	374	342	0.46	35
Tephrosia lupinifolia	968	170	200	260	0.61	22
Zornia glochidiata	971	145	184	533	2.68	55
Lablab purpureus	965	100	240	431	2.4	72
SEM	03.1	21.4	13.7	69.0	1.09	4.74
P-value	NS	*	***	NS	NS	**

Table 2: Differences in chemical composition (g/kg) of different wild legume species from Ngamiland. DM = dry matter; ADF = acid detergent fibre; NDF = neutral detergent fibre; CP = crude protein; SEM = standard error of mean

Parameters	DM	Ash	CP	ADF	NDF
Chamaecrista abscus	940.0	306.5	226.8±24.9	229.5	362.5
Crotalaria sphaerocarpa	930.0	128.0	159.8±24.9	142.0	316.0
Indigofera sp.	930.0	152.0	362.5±35.2	96.5	268.5
Tephrosia sp.	950.0	132.0	343.0±24.9	174.5	362.5
SEM	8.7	12.9		22.7	12.8
P-value	NS	**	*	NS	*

Condensed tannins and gas production

Only samples from Tswapong were also tested for condensed tannins according to Makkar (2000) and expressed as leucocyanidin equivalents. Total gas production of the Tswapong samples was determined after incubation of a sample with rumen fluid in glass syringes according to modified methods of Menke & Steingass (1988) to index digestibility.

Data analysis

Data from the two sites were not compared because of differences in the plant species sampled. This is because the same plants were not found growing at the two sites. Differences in the nutritive value of the sampled species were tested by analysis of variance (ANOVA) using general linear models (GLM) implemented in SAS (2002–2008), and results are reported as least-square means ± standard error of mean (SEM). A simple correlation analysis between crude protein and condensed tannins was tested using Pearson (SAS, 2002–2008).

Results

The nutritive value of wild legumes from Tswapong is shown in Table 1. There was no difference in NDF or condensed tannins concentration among the legumes. *C. rotundifolia* and *T. purpurea* had the highest CP while *Zornia glochidiata*

had the least. No correlation (r = –0.26; P = 0.53) was detected between condensed tannins and crude protein.

Results from samples from Ngamiland are presented in Table 2. There was a tendency (P = 0.057) toward variations in ADF levels among plant species, while other parameters differed (from $P < 0.01$ to $P < 0.05$) among the legume plants.

Discussion

Chemical composition

Crude protein (CP), which is generally used as an index of quality in ruminant diets, averaged 270.4 g/kg for plants from Tswapong, with *Tephrosia purpurea* having the highest concentration of CP and *Zornia glochidiata* having the lowest. Legumes from Ngamiland had an average CP of 273.0 g/kg, with *Indigofera* sp. having the highest levels and *Crotalaria sphaerocarpa* having the lowest. These concentrations of CP are similar to and/or better than that of *Lablab purpureus*, a fodder crop commonly offered to livestock in small-holder farm in southern Africa. However, the apparently high CP levels in the wild herbaceous legumes species compared to most fodder plants may be misleading, as the high toxic amino acids and other plant nitrogenous secondary metabolites could mean that animals would either not consume the material or not utilise it effectively (Hassen et al., 2008). The availability of protein in sufficient amounts to the animal is controlled by feed intake and ease of digestion by rumen microorganisms and the animal's own enzymes. Therefore, the issue of the biomass yield of these legumes is important for consideration for future utilisation as fodder crops for livestock. In addition, high fibre/lignin content binding to the protein may be detrimental to the availability of the protein, and according to Stolter et al. (2018), these factors will also negatively affect feed intake and other feeding activities. Therefore, future work with these herbaceous plants should investigate the extent of bonding of lignin and other anti-nutritive compounds with protein. Ash content for samples from Tswapong was high for *Tephrosia purpurea* while the level of ash in *Zornia glochidiata* was the lowest. For Ngamiland samples, ash content was high for *Chamaecrista abscus,* and the lowest was observed for *Crotalaria sphaerocarpa*. These values for ash are higher than for the basal forage *Eleusine coracana* (Madibela & Modiakgotla, 2004), suggesting that legumes would supply more minerals than basal forage and are suitable to supply minerals to ruminants. Fibre components varied with location and with forage type; this was not tested statistically, as the same plants were not growing in the different sites, but distinct trends were observed between Tswapong samples and those obtained from Ngamiland. For example, in samples obtained from Tswapong, neutral detergent fibre (NDF) averaged 404 g/kg, with the highest concentration noted for *Zornia glochidiata*. These values are higher than in samples obtained from Ngamiland, which averaged 327.4 g/kg ash. The NDF levels for samples harvested from Ngamiland were lower for *Indigofera* sp. and higher for both *C. abscus* and *Tephrosia* sp. Ngamiland is recognised for its higher rainfall (≈ 600 mm/year) than eastern Botswana (≈ 420 mm/year) (Bernard et al., 2017; Parida & Moalafhi, 2008), where Tswapong is located. This may be the reason for differences observed, since location influences the availability of soil moisture and hence forage quality. In areas with higher rainfall, plants do not accumulate fibre quickly but maintain a high protein content for relatively longer periods than in areas with low rainfall. Effect of site was, however not tested in this study. The growth stages of these plants were also not studied, and sampling happened once in the middle of the growth season during flowering (Bernard et al., 2017). This is important because as plants mature, concentrations of fibre components increase, influencing the fibre content in forages. The concentrations of NDF observed for samples from Ngamiland are within the values noted for effective rumen activity and animal performance. According to Harris (2003), the beneficial aspects of dietary fibre are due to its effect on regurgitation (cud chewing), chewing, salivation, rumen pH (acidity), and rumen function. However, higher NDF such as that found in *Zornia glochidiata* and *C. rotundifolia* may hinder dry matter intake as a result of restricted rumen fill if the forages are offered as sole feed, which is unlikely since it is anticipated that they will be utilised as supplements. With regard to acid detergent fibre (ADF), samples harvested from Ngamiland had lower ADF concentrations, averaging 160.6 g/kg, with the lowest observed for *Indigofera* sp. Seguin et al. (2002) observed that soil moisture deficit increased ADF levels. Under the circumstances described above, higher ADF is bound to affect digestibility (Harris Jr., 2003) when such plants are fed to ruminants. In contrast, Seguin et al. (2002) found that when ADF is increased while ADL content was reduced, led to increase forage digestibility.

In vitro gas production

Total gas procedure by Menke & Steingass (1988) estimate fermentation processes in the rumen, and the gas measured is regarded as waste from such processes. The measurement gives insight into the extent of the degradability of a feed material and its degradation rate. Gas produced during incubation was higher for *Z. glochidiata* (55 ml/0.5 g) and lower for *T. lupinifolia* (22 ml/0.5 g), while *C. rotundifolia* and *T. purpurea* both produce 35 ml/0.5 g of gas. The interpretation of this result is that *Z. glochidiata* would undergo higher degradation in the rumen of ruminants than *T. lupinifolia*, even though the former has both higher fibre (NDF and ADF) and a higher concentration of condensed tannins than the latter. Condensed tannins have been noted to reduce degradability (Gemeda & Hassen, 2015) by binding to useful substrates in the rumen and denying microorganisms the required nutrients for growth and fermentative processes. This binding of nutrients by CTs may, however, be beneficial if the concentration of condensed tannins is less than 5.0 g/kg, as tannin-bound protein escaping microbial degradation will increase the amount of protein supplied post-ruminally. This increase in protein can be used for productive purposes such as growth, milk production, and immune function. Results of Hassen et al. (2008) showed *in vitro* organic matter digestibility to be moderate for *Indigofera* spp. in

South Africa. A review of literature by Abdullah & Kumalasari (2011) in Indonesia indicated that *Indigofera* spp. have a high protein (27–29%) and mineral (Ca, P, Mg, and Zn) content, a moderate NDF structure, and a high digestibility value for ruminants (67–81%). These values of CP for *Indigofera* spp. are comparable to some accessions tested by Hassen et al. (2008) in South Africa, where they found medium to high levels of CP (15.9%–29.9%). Condensed tannins also reduce the yield of methane gas in the rumen (Gemeda & Hassen 2015; Piñeiro-Vázquez et al., 2015). Alternatively, the high gas production by *Z. glochidiata* regardless of its high fibre content may be due to the disproportional production of methane gas compared to carbon dioxide. Forage with relatively high cell wall content produces high amounts of methane in the rumen. In the current study, methane yield was not estimated, and future studies need to incorporate this important parameter because of its current and future implications in agriculture.

Conclusions

The legumes investigated have high protein and mineral content, making them suitable candidate forages for supplying the nutrients found in low quantities in basal low-quality hay, straw, or crop residues. Different amounts of gas production during *in vitro* incubation were observed, probably as a result of differences in fibre and condensed tannin concentration. Forages with high gas production suggest high fermentation extent or rate and thus high *in vitro* digestibility, and therefore would be expected to supply more nutrients to ruminants. Measurements of methane and digestibility as well as feeding studies are recommended for future experiments to obtain information that would inform strategies on how best to utilise these plants as protein supplements for livestock.

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References

Abdullah, L. & Kumalasari N. R. (2011) Amino acid contents of *Indigofera arrecta* leaves after application of foliar fertilizer. *Journal of Agricultural Science and Technology A,* **1**, 1224–1227

AOAC (1996) Official methods of analysis. Association of Analytical Chemists, Washington, DC, USA.

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis* 10.1007/s13199-017-0515-2

Chen, Y., Yan, T., Gao, C., Cao, W. & Huang, R. (2014) Natural products from the genus *Tephrosia*. *Molecules*, **19**, 1432–1458.

Gemeda, B.S. & Hassen, A. (2015) Effect of tannin and species variation on in vitro digestibility, gas, and methane production of tropical browse plants. *Asian-Australasian Journal of Animal Sciences*, **28**, 188–199.

Harris, Jr., B. (2003). The importance of fiber in feeding dairy cattle. Dairy production guide. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. http://edis.ifas.ufl.edu

Hassen, A., Rethman, N.F. Apostolides, G.Z. & van Niekerk, W.N. (2008) Forage production and potential nutritive value of 24 shrubby *Indigofera* accessions under field conditions in South Africa. *Tropical Grasslands*, **42**, 96–103.

Hoste, H., Martinez-Ortiz-De-Montellano, C., Manolaraki, C.F., Brunet, S., Ojeda-Robertos, N., Fourquaux, I., Torres-Acosta, J.F.J. & Sandoval-Castro, C.A. (2012) Direct and indirect effects of bioactive tannin-rich tropical and temperate legumes against nematode infections. *Veterinary Parasitology*, **186**, 18–27.

Jensen, T.L. (2012) Livestock foraging behavior in response to sequence and interactions among alkaloids, tannins, and saponins. PhD thesis, Utah State University, Logan, UT, USA.

Lamy, E., Rawel, H., Schweigert, F.J., Silva, F.C., Ferreira, A., Costa, A.R., Antunes, C., Almeida, A.M., Coelho, A.V. & Sales-Baptista, E. (2011) The effect of tannins on Mediterranean ruminant ingestive behaviour: the role of the oral cavity. *Molecules,* **16**, 2766–2784.

Madibela, O.R. & Modiakgotla, E. (2004) Chemical composition and in vitro dry matter digestibility of indigenous finger millet (*Eleusine coracana*) in Botswana. *Livestock Research for Rural Development*, **6**, article 26. http://www.lrrd.org/lrrd16/4/madi16026.htm

Makkar, H.S. (2000) Quantification of tannins in tree foliage. A laboratory manual for the FAO/IAEA coordinated research project on use of nuclear and related techniques to develop simple tannin assays for predicting and improving the safety and efficiency of feeding ruminants on tanniferous tree foliage IAEA Working Document. IAEA, Vienna.

Menke, K.H. & Steingass, H. (1988) Estimation of the energetic feed value obtained by chemical analysis and in vitro gas production using rumen fluid. *Animal Resources Development,* **28**, 7–55.

Naumann, H.D., Armstrong, S.A., Lambert, B.D., Muir, J.P., Tedeschi, L.O. & Kothmann, M.M. (2014) Effect of molecular weight and concentration of legume condensed tannins on *in vitro* larval migration inhibition of *Haemonchus contortus*. *Veterinary Parasitology*, **199**, 93–98.

Obopile, M., Karabo, O., Pearl Tshipinare, B., Losologolo, M., Bernard, N., Ngwako, S., Batlang, U., Nnaniki Mashungwa, G., Tselaesele, N. & Pule-Meulenberg, F. (2018) Increasing yields of cereals: benefits derived from intercropping with legumes and from the associated bacteria. This volume.

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-Moments and radial basis function network. *Physics and Chemistry of the Earth,* **33**, 614–620.

Piñeiro-Vázquez, A.T., Canul-Solís, J.R., Alayón-Gamboa, J.A., Chay-Canul, A.J., Ayala-Burgos, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F.J. & Ku-Vera, J.C. (2015) Potential of condensed tannins for the reduction of emissions of enteric methane and their effect on ruminant productivity. *Archivos de Medicina Veterinaria,* **47**, 263–272.

Seguin, P., Mustafa, A.F. & Sheaffer, C.C. (2002) Effects of soil moisture deficit on forage quality, digestibility, and protein fractionation of Kura clover. *Journal of Agronomy and Crop Science*, **188**, 260–266.

Silanikove, N., Pevevolotsky, A. & Provenza, F.D. (2001) Use of tannin-binding chemical to assay for tannins and their negative postingestive effects in ruminants. *Animal Feed Science and Technology*, **91**, 69–81.

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018) Forage quality and availability for large herbivores. This volume.

Tarawali, S.A. (1995) Evaluation of *Chamaecrista rotundifolia* accessions as a fodder resource in subhumid Nigeria. *Tropical Grasslands,* **29**, 129–133.

Tedeschi, L.O., Ramirez-Restrepo, C.A. & Muir, J.P. (2014) Developing a conceptual model of possible benefits of condensed tannins for ruminant production. *Animal*, **8**, 1095–1105.

Villalba, J.J. & Landau, S.Y. (2012) Host behaviour, environment and ability to self-medicate. *Small Ruminant Research,* **103**, 50–59.

Waghorn, G.C., Ulyatt, M.J., John, A. & Fisher, M.T. (1987) The effect of condensed tannins on the site of digestion of amino acids and other nutrients in sheep fed on *Lotus corniculatus* L. *British Journal of Nutrition*, **57**, 115–126.

Wilson, R.A. (2009) Fit for purpose — the right animal in the right place. *Tropical Animal Health and Production*, **41**, 1081–1090.

References [CrossRef]

Abdullah, L. & Kumalasari N. R. (2011) Amino acid contents of *Indigofera arrecta* leaves after application of foliar fertilizer. *Journal of Agricultural Science and Technology A*, **1**, 1224–1227

AOAC (1996) Official methods of analysis. Association of Analytical Chemists, Washington, DC, USA.

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis*. CrossRef

Chen, Y., Yan, T., Gao, C., Cao, W. & Huang, R. (2014) Natural products from the genus *Tephrosia*. *Molecules*, **19**, 1432–1458. CrossRef

Gemeda, B.S. & Hassen, A. (2015) Effect of tannin and species variation on in vitro digestibility, gas, and methane production of tropical browse plants. *Asian-Australasian Journal of Animal Sciences*, **28**, 188–199. CrossRef

Harris, Jr., B. (2003). The importance of fiber in feeding dairy cattle. Dairy production guide. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. http://edis.ifas.ufl.edu

Hassen, A., Rethman, N.F. Apostolides, G.Z. & van Niekerk, W.N. (2008) Forage production and potential nutritive value of 24 shrubby *Indigofera* accessions under field conditions in South Africa. *Tropical Grasslands*, **42**, 96–103.

Hoste, H., Martinez-Ortiz-De-Montellano, C., Manolaraki, C.F., Brunet, S., Ojeda-Robertos, N., Fourquaux, I., Torres-Acosta, J.F.J. & Sandoval-Castro, C.A. (2012) Direct and indirect effects of bioactive tannin-rich tropical and temperate legumes against nematode infections. *Veterinary Parasitology*, **186**, 18–27. CrossRef

Jensen, T.L. (2012) Livestock foraging behavior in response to sequence and interactions among alkaloids, tannins, and saponins. PhD thesis, Utah State University, Logan, UT, USA.

Lamy, E., Rawel, H., Schweigert, F.J., Silva, F.C., Ferreira, A., Costa, A.R., Antunes, C., Almeida, A.M., Coelho, A.V. & Sales-Baptista, E. (2011) The effect of tannins on Mediterranean ruminant ingestive behaviour: the role of the oral cavity. *Molecules*, **16**, 2766–2784. CrossRef

Madibela, O.R. & Modiakgotla, E. (2004) Chemical composition and in vitro dry matter digestibility of indigenous finger millet (*Eleusine coracana*) in Botswana. *Livestock Research for Rural Development*, **6**, article 26. http://www.lrrd.org/lrrd16/4/madi16026.htm

Makkar, H.S. (2000) Quantification of tannins in tree foliage. A laboratory manual for the FAO/IAEA coordinated research project on use of nuclear and related techniques to develop simple tannin assays for predicting and improving the safety and efficiency of feeding ruminants on tanniferous tree foliage IAEA Working Document. IAEA, Vienna.

Menke, K.H. & Steingass, H. (1988) Estimation of the energetic feed value obtained by chemical analysis and in vitro gas production using rumen fluid. *Animal Resources Development*, **28**, 7–55.

Naumann, H.D., Armstrong, S.A., Lambert, B.D., Muir, J.P., Tedeschi, L.O. & Kothmann, M.M. (2014) Effect of molecular weight and concentration of legume condensed tannins on *in vitro* larval migration inhibition of *Haemonchus contortus*. *Veterinary Parasitology*, **199**, 93–98. CrossRef

Obopile, M., Karabo, O., Pearl Tshipinare, B., Losologolo, M., Bernard, N., Ngwako, S., Batlang, U., Nnaniki Mashungwa, G., Tselaesele, N., Pule-Meulenberg, F. (2018) Increasing yields of cereals: benefits derived from intercropping with legumes and from the associated bacteria. This volume. CrossRef

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-Moments and radial basis function network. *Physics and Chemistry of the Earth*, **33**, 614–620. CrossRef

Piñeiro-Vázquez, A.T., Canul-Solís, J.R., Alayón-Gamboa, J.A., Chay-Canul, A.J., Ayala-Burgos, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F.J. & Ku-Vera, J.C. (2015) Potential of condensed tannins for the reduction of emissions of enteric methane and their effect on ruminant productivity. *Archivos de Medicina Veterinaria*, **47**, 263–272. CrossRef

Seguin, P., Mustafa, A.F. & Sheaffer, C.C. (2002) Effects of soil moisture deficit on forage quality, digestibility, and protein fractionation of Kura clover. *Journal of Agronomy and Crop Science*, **188**, 260–266. CrossRef

Silanikove, N., Pevevolotsky, A. & Provenza, F.D. (2001) Use of tannin-binding chemical to assay for tannins and their negative postingestive effects in ruminants. *Animal Feed Science and Technology*, **91**, 69–81. CrossRef

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume. CrossRef

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018) Forage quality and availability for large herbivores. This volume. CrossRef

Tarawali, S.A. (1995) Evaluation of *Chamaecrista rotundifolia* accessions as a fodder resource in subhumid Nigeria. *Tropical Grasslands*, **29**, 129–133.

Tedeschi, L.O., Ramirez-Restrepo, C.A. & Muir, J.P. (2014) Developing a conceptual model of possible benefits of condensed tannins for ruminant production. *Animal*, **8**, 1095–1105. CrossRef

Villalba, J.J. & Landau, S.Y. (2012) Host behaviour, environment and ability to self-medicate. *Small Ruminant Research*, **103**, 50–59. CrossRef

Waghorn, G.C., Ulyatt, M.J., John, A. & Fisher, M.T. (1987) The effect of condensed tannins on the site of digestion of amino acids and other nutrients in sheep fed on *Lotus corniculatus* L. *British Journal of Nutrition*, **57**, 115–126. CrossRef

Wilson, R.A. (2009) Fit for purpose — the right animal in the right place. *Tropical Animal Health and Production*, **41**, 1081–1090. CrossRef