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Research article

Nutritional composition of browse and diets fed to ungulates at the Breeding Centre for Endangered Arabian Wildlife

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Abstract
Captive browsing ruminants are particularly susceptible to gastrointestinal disorders, and inappropriate diets are an underlying factor. This study investigated the nutritional composition of browse and pelleted feedstuffs used in an Arabian facility and compared nutrient intake against current recommendations for exotic ungulates. Additionally, retrospective evaluation of post-mortem findings with regard to gastrointestinal pathologies was conducted (n = 497). Samples of browse from seven species of locally cultivated plants, as well as three brands of pelleted feeds, were submitted for laboratory analysis. Following a five-day feed intake study, nutrient intake was calculated. Only moderate variation was seen among browse species' composition compared to previous reports. However, significant variation occurred between plant fractions (stem, leaves and seed pods) for neutral detergent fibre and several minerals. Browse comprised over half of the metabolisable energy (ME) intake of Arabian tahr (*Arabitragus jayakari*), but only 11% of ME for Arabian gazelle (*Gazella gazella cora*) and Dorcas gazelle (*G. gazella dorcas*). However, no relationship could be detected between gastrointestinal disease and browse provision in these species. No nutrient deficiencies were identified, but the Arabian tahr diet exceeded the recommended amount of crude protein, and both gazelle diets provided excess iron, manganese, copper and zinc. These mineral excesses are the subject of on-going investigations in order to better balance the diets offered. Moreover, the high starch content of pelleted diets evaluated in the current study (22–29%, on a dry matter basis) indicates that a reduction in the proportional provision of pellets would improve the diet suitability, particularly for the gazelles. This study highlights a number of areas for potential improvement, although further research is required to fully understand the implications of these findings.

Introduction

The diet of free-ranging ungulate browsers, including those living in arid regions, typically includes primarily dicotyledonous plant material such as leaves and twigs (Clauss and Dierenfeld 2008; Wronski and Schulz-Kornas 2015). In an ideal scenario, nutritional management of these animals in captivity would include provision of a "natural diet", (i.e. one that is equivalent to that consumed by free-ranging conspecifics). In order to accommodate the digestive physiology of these ruminants, the provision of forage (unprocessed, high-fibre items) is considered vital (Clauss and Dierenfeld 2008). As such, a diet which is high in fibre, contains a moderate amount of protein, and is not too rapidly fermentable or highly digestible is considered to best represent their natural diet (Clauss et al. 2003a; Clauss and Dierenfeld 2008).

However, duplication of any species' natural dietary intake can be challenging for captive animal managers (Graffam et al. 1997). The constraints of captivity, including ingredient supply, storage, and a paucity of species-specific knowledge of wild animal feeding ecology, often dictate the use of alternative feeds. Pelleted feeds are a convenient method of ensuring that animals' predicted nutritional requirements are met (Gill & Cave-Browne 1988; Oftedal et al. 1996). However, pellets formulated for domestic ungulates (i.e. grazers rather than browsers) may contain highly digestible fibre sources, high nitrogen and/or starch fractions that can be detrimental to gastrointestinal tract health (Clauss and Dierenfeld 2008; Koutsos 2009), whilst the physical structure of pellets (i.e. fine particle size) has been shown to reduce rumination activity (Welch and Smith 1971). As such, leafy and/or woody forage supplementation (i.e. browse and hays), is relatively common in zoos around the world (Lintzenich and Ward 1997); benefits include diet diversity and the encouragement of natural foraging behaviours (Morgan 2006), while providing an inexpensive form of vegetable protein and essential dietary minerals, fatty acids and vitamins (Anbarasu et al. 2003, Grant et al. 2002; Clauss et al. 2003a).

Given the important role that nutrition plays in animal health, periodic reviews of a captive facility's dietary provision is considered vital. In contrast to the extensive information available on domestic ungulate diets and nutrition, little is known about suitable rations of leaf material and dry fodder for many species of rare captive-bred ungulates (Clauss et al. 2003a). Therefore, knowledge of nutritional requirements in domestic ungulates is typically used as the foundation for designing diets for captive-bred animals (Oftedal et al. 1996).

The Breeding Centre for Endangered Arabian Wildlife (BCEAW, Sharjah, United Arab Emirates, UAE) houses six non-domestic ungulate species, represented by between 20 and 150 animals each, which are held in large semi-natural enclosures. The collection includes species classified by the IUCN as Endangered (Arabian tahr, *Arabitragus jayakari*) and Vulnerable (Arabian oryx, *Oryx leucoryx*; Nubian ibex, *Capra nubiana*; Arabian mountain gazelle, *Gazella g. cora*; Arabian sand gazelle, *G. subgutturosa marica*; and Dorcas gazelle, *G. g. dorcas*). The BCEAW uses a range of cultivated indigenous and non-indigenous plants grown in the local vicinity to supply browse to its captive ungulates, which is provided in conjunction with commercially produced pelleted feeds designed for sheep and gazelle.

Combined with an interest in evaluating the suitability of the diet offered against current recommendations and recent advances in our understanding of diet-related disease factors, it was deemed important to determine the nutrient intake of captive herbivores at the BCEAW (as per Nijboer and Dierenfeld 1996; Graffam et al. 1997; Livingston et al. 2007). The aims of this study were therefore to determine the nutritional composition of browse and pelleted feedstuffs used at BCEAW, and compare the calculated total dietary intake of selected nutrients against current recommendations for exotic ungulates, as well as to evaluate diets retrospectively with regard to identified nutritional pathologies from historic necropsy records.

Methods

Diet ingredients

Leaves (including petioles and edible unlignified lateral shoots to which leaves were attached), woody (lignified) parts (less palatable stem/twigs, branches or twigs) and seed pods (including seeds) were sampled from seven locally-grown plant species: date palm (*Phoenix dactylifera*), ghaf tree (*Prosopis cineraria*), *Acacia tortilis*, *A. nilotica*, sidr (*Zizyphus spina-christi*), leucaena (*Leucaena leucocephala*) and *Pithecellobium dulce.* At least five different plants were sampled per species and analysed as a single pooled sample for each species. Only the portion of the plant known to be offered to ungulates was sampled, and each component was analysed separately. Leaf-to-stem/twig ratios were calculated for each species using a sub-sample of each species (minimum three branches) where leaves, edible stem/twigs and inedible stem/twigs (as observed during feeding studies) were separated and weighed prior to drying.

Following weighing and overnight drying in convection ovens (maximum 60° C) to determine moisture content, browse samples were transported to Dairy One Forage Laboratory (Ithaca, NY, USA) for analyses. Three brands of pelleted diet have been used over the past 15 years, each for variable durations; at the time of the study all gazelle species were fed a pellet designed for gazelles ("gazelle" pellets), whereas Arabian oryx, Nubian ibex and Arabian tahr were fed a pelleted diet designed for sheep (two alternating brands; "Brand A" and "Brand B"). Samples of each pelleted feedstuff (representing a combined sample from a minimum of five separate bags of each brand) were simultaneously submitted for analyses.

Two types of mineralised salt licks were available to all ungulates except the Arabian tahr on a continual basis. Only one brand (A) was provided to Arabian tahr. Intake/utilisation of these blocks was not determined empirically, although animals of each species were regularly observed to use them.

Laboratory analysis

Analyses included dry matter (DM; Goering and Van Soest 1970), crude protein (CP; AOAC 990.03), crude fat (AOAC 2003.05), non-fibre carbohydrates (NFC; by difference as 100% - (CP% + (NDF% - NDICP%) + Fat% +Ash%)), and ash (AOAC 942.05). A more comprehensive assessment of the carbohydrate (CHO) fractions included acid detergent fibre (ADF; ANKOM Technology Method 5), neutral detergent fibre (NDF; ANKOM Technology Method 1): both ADF and NDF are reported without correction for ash in residues, lignin (sulphuric acid; ANKOM Technology Method 9), starch (YSI 2700 SELECT Biochemistry Analyzer), and ethanol soluble carbohydrates (Hall et al. 1999). Protein fraction analysis also included acid detergent insoluble CP (ADICP; ADF residue analysed using a Leco TruMac N Macro Determinator) and neutral detergent insoluble CP (NDF performed without sodium sulphite and then residue analysed using a Leco TruMac N Macro Determinator). Total digestible nutrients (TDN; sum of the digestible protein, digestible non-structural carbohydrates, digestible NDF and 2.25X the digestible fat) and ME (ruminants) values were also calculated by the independent laboratory, using the Weiss Ohio State University multi-component equations for maintenance levels (Weiss et al. 1992) and NRC (2001), respectively. Selected minerals were also analysed (Ca, P, Mg, K, Na, Fe, Zn, Cu, Mn and Mo; analysed by ICP following the CEM Application Notes for Acid Digestion, CEM, Matthews, NC).

Post-mortem findings

The post-mortem database maintained by the veterinary department at the BCEAW was accessed to determine the number of each species diagnosed with a digestive disorder at the time of death. Findings were evaluated for 176 Arabian mountain gazelles, 74 Arabian oryx, nine Arabian tahr, 94 Nubian ibex and 144 sand gazelles that died between 2000 and 2013. The percentage of animals with an identified digestive disorder at the time of death was compared to previously published data for the same, or similar, species from a South African facility (Gattiker et al. 2014).

Diet evaluation

With the exception of Arabian tahr, ungulates at BCEAW were provided with a mixture of *P. dulce* browse and pellets as a daily staple diet. Other species of browse were only fed opportunistically according to seasonal variation and were therefore excluded from the evaluation of the total diet. Basal diets offered to animals are described in Table 1 and included (on a DM basis) 54% browse for both Arabian mountain gazelle and Dorcas gazelle but only 33% browse for Arabian oryx, 30% browse for sand gazelle and 29% browse for Nubian ibex. The diet offered to Arabian tahr (DM basis) comprised 59% *P. dulce* browse, 7.5% ghaf seed pods, 2.9% ghaf tree leaves, 3.3% *Z. spini-christi* leaves, 26% pellets and 1.2% fruit and vegetables.

A five-day intake study was conducted to determine actual consumption. Due to the use of mixed-species exhibits at BCEAW, only three species were available for the feed intake study: Arabian tahr (n=2), Dorcas gazelle (n=27) and Arabian gazelle (n=30). Animals were all of adult age, of good health status, and in

Table 1. Daily diets offered to captive ungulates at BCEAW, Sharjah, United Arab Emirates.

Species	Conservation status	Median body wt[1] (kg)	Diet: concentrate	Diet: browse	Browse (g/kg BW; As fed)	Browse (g/kg BW; DM)	Pellet (g/kg BW; As fed)	Pellet (g/kg BW; DM)	Ratio browse: pellet (As-fed)	Ratio browse: pellet (DM)
Arabian tahr *Hemitragus jayakari*	Endangered	25	Sheep pellet	*Pithecellobium dulce* *Prosopis cineraria* *Zizyphus spina-christi*	22.0	7.7	2.8	2.65	7.9	3.0
Arabian oryx *Oryx leucoryx*	Vulnerable	90	Sheep pellet	*P. dulce*	14.3	5.0	10.9	10.0	1.3	0.5
Nubian ibex *Capra nubiana*	Vulnerable	38	Sheep pellet	*P. dulce*	18.7	6.6	17.9	16.3	1.0	0.4
Arabian mountain gazelle *Gazella g. cora*	Vulnerable	12	Gazelle pellet	*P. dulce*	96.0	33.8	32.2	29.4	3.0	1.25
Arabian sand gazelle *G. subgutturosa marica*	Vulnerable	16	Gazelle pellet	*P. dulce*	29.3	10.3	26.6	24.3	1.1	0.4
Dorcas gazelle *Gazella g. dorcas*	Vulnerable	13	Gazelle pellet	*P. dulce*	107.1	37.7	35.9	32.7	3.0	1.2

[1] Estimated from published data for adult animals (International Species Information System 2014)

good body condition at the time of the study. None of the animals were pregnant or lactating during the study, with the exception of nine pregnant Arabian gazelles (gestation stage ranging from early (1 week) to mid-stage (4–5 months)). Calculated feed intake was determined by subtracting orts from offered amount (on an as-fed basis) and then adjusted according to measured desiccation factors. Average total daily intake per animal was determined for each species.

Nutrient data for each browse species and pelleted feeds were entered into Zootrition® software (V2.7, St. Louis, MO, USA, 2014) after laboratory analyses. In cases where acid detergent insoluble CP (ADICP) accounted for more than 10% of CP, the

Table 2. Dry matter (DM), crude protein (CP), adjusted CP (ACP), acid detergent insoluble CP (ADICP), crude fat, ash content, total digestible nutrients (TDN) of seven species of browse and three pelleted feedstuffs fed to captive ungulates at BCEAW, United Arab Emirates. Leaf-to-edible stem/twig (L-to-E) and edible-to-inedible (E-to-I) fraction ratios are also presented for the browse species. All data (except dry matter) presented on a %DM basis.

Feed sample	Dry matter	CP	ACP[1]	ADICP	NDICP	Crude fat	Ash	TDN[2]	L-to-E ratio[3]	E-to-I ratio[4]
L. leucocephala leaves	36.7	23.4	19.3	4.1	12.1	5.4	9.7	63.0	6.5	4.9
L. leucocephala stems/twigs	42.0	13.1	11.7	1.4	3.6	2.9	6.6	52.0		
L. leucocephala seed pods	28.5	29.5	27.5	2.0	7.1	1.8	6.7	65.0		
Phoenix dactylifera leaves	49.6	5.8	4.40	1.4	1.8	4.6	20.0	50.0	n/a	4.0
A. tortilis leaves	55.7	17.3	14.8	2.5	9.4	5.9	6.8	68.0	n/a	0.3
A. nilotica leaves	50.4	12.0	13.4	1.3	5.3	6.1	8.0	74.0	2.40	0.9
A. nilotica seed pods	32.4	14.5	13.4	1.1	2.5	3.2	6.1	71.0		
C. zizyphus spina-christi leaves	49.8	11.4	8.7	2.7	6.5	4.1	10.5	66.0	16.84	9.1
Pithecellobium dulce leaves	35.2	28.4	24.8	3.6	9.9	5.7	6.9	66.0	8.45	1.4
Pithecellobium dulce seed pods[5]	29.8	15.9	14.6	1.3	2.9	5.6	5.5	70.0		
Pithecellobium dulce seed pods[6]	23.8	18.1	16.8	1.3	25.7	7.6	5.8	77.0		
Prosopsis cineraria leaves	44.6	11.3	4.9	6.4	7.6	5.1	11.3	63.0	9.4	6.1
Prosopsis cineraria stems/twigs	46.9	11.2	7.9	3.3	51.7	2.4	6.0	44.0		
Prosopsis cineraria seed pods	85.1	16.8	15.5	1.3	2.7	1.8	6.1	64.0		
Brand A sheep pellets	91.1	14.4	14.0	0.4	1.8	4.1	8.5	73.0		
Brand B sheep pellets	91.2	15.5	15.0	0.5	1.9	3.1	9.2	69.0		
Gazelle pellets	91.8	15.4	14.9	0.5	1.8	2.6	11.7	64.0		

[1]Adjusted CP = (Crude protein – Acid Detergent Insoluble CP); [2]TDN calculated as per Weiss et al. (1992); [3]Edible stem/twig determined according to personal observation of ungulate feeding habits at the BCEAW (J. Strick). [4]Edible includes both leaves and edible stems/twigs in one fraction, versus inedible (woody) fraction. N/A = not applicable since only the leaves were edible.[5]Yellow (sun-ripened).[6]Green (on the tree)

Table 3. Carbohydrate fraction characterisation (%) and calculated metabolisable energy content (kJ/kg) of seven species of browse and three pelleted feedstuffs fed to captive ungulates at BCEAW, United Arab Emirates. All data presented on a dry matter basis.

Feed sample	Acid detergent fibre, %	Neutral detergent fibre, %	Non fibre carbohydrates, %	Lignin, %	Starch, %	Ethanol soluble carbohydrates, %	NDSF[1], %	Metabolisable energy (MJ/kg)[2]
L. leucocephala leaves	23.9	32.6	36.4	7.9	1.1	4	31.4	10.5
L. leucocephala stem/twigs	23.2	34.8	38.7	11.3	0.6	4.3	33.9	11.2
L. leucocephala seeds	41.8	55.7	25.2	12.8	0.8	4.8	19.7	8.0
Phoenix dactylifera leaves	44.7	48.8	32.6	14.9	0.4	14.8	7.4	7.3
A. tortilis leaves	28.5	30.4	49	13.9	1.5	8	39.5	11.0
A. nilotica leaves	20.1	21.8	57.5	7.2	0.9	7.7	48.9	12.0
A. nilotica seeds	19.3	27.3	51.5	5.7	1.4	10.1	40.0	11.4
C. zizyphus spina-christi leaves	13.2	22.6	57.9	12.3	0.8	12.7	44.4	10.3
Pithecellobium dulce leaves	27.1	37.1	31.9	9.7	2.7	7.8	21.4	11.3
Pithecellobium dulce seeds[3]	22.9	33.6	42.3	7.1	4.7	24.7	12.9	11.5
Pithecellobium dulce seeds[4]	17.1	25.7	47.1	5.8	13.2	15.1	40.3	12.9
Prosopsis cineraria leaves	18.3	25.3	54.5	9.4	0.9	9.1	44.6	9.5
Prosopsis cineraria stem/twigs	35.9	51.7	33.5	22.6	5.9	8	66.5	6.4
Prosopsis cineraria seeds	23.5	34.1	43.8	7.8	0.8	24.3	18.8	10.3
Brand A sheep pellets	17.5	29.9	44.2	4	27.6	7.5	9.2	11.3
Brand B sheep pellets	12.5	28.2	47.6	3.5	29.2	6.4	11.1	11.8
Gazelle pellets	22.8	35.6	38.2	4.5	21.7	7.1	7.7	10.3

[1] Neutral detergent soluble fibre (NDSF) calculated as NDSF = 100 – (ash + (NDF – NDICP) + CP + fat) – (ESC + starch), where NDF = neutral detergent fibre, NDICP = neutral detergent insoluble crude protein, CP = crude protein, ESC = ethanol soluble carbohydrates (representing sugar). [2] Calculated from the NRC (2001) equation for dairy cattle. [3] Yellow (sun-ripened). [4] Green (on the tree).

Table 4. Mineral composition of seven species of browse and three pelleted feedstuffs fed to captive ungulates at BCEAW, United Arab Emirates. All data presented on a dry matter (DM) basis.

	Ca (%)	P (%)	Mg (%)	K (%)	Na (%)	Fe (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Mn (mg/kg)	Mo (mg/kg)
L. leucocephala leaves	2.33	0.18	0.36	1.37	0.01	327	23	7.0	30	0.1
L. leucocephala stem/twigs	0.56	0.33	0.21	2.34	0.01	150	31	8.0	20	0.9
L. leucocephala seeds	0.89	0.24	0.28	1.98	0.04	135	33	9.0	13	1.1
Phoenix dactylifera leaves	0.96	0.05	0.29	0.42	0.03	658	28	5.0	33	0.8
A. tortilis leaves	1.31	0.17	0.31	1.23	0.0	593	19	5.0	60	0.3
A. nilotica leaves	1.91	0.10	0.28	0.82	0.14	740	33	8.0	41	0.3
A. nilotica seeds	0.88	0.20	0.23	1.76	0.02	127	32	10.0	20	1.0
Zizyphus spina-christi leaves	2.65	0.15	0.40	1.19	0.56	340	22	7.0	26	0.2
Pithecellobium dulce leaves	1.01	0.25	0.30	1.60	0.18	278	29	12.0	26	0.2
Pithecellobium dulce seeds[1]	0.19	0.19	0.12	2.10	0.01	86.0	23	8.0	11	0.2
Pithecellobium dulce seeds[2]	0.16	0.27	0.12	2.26	0.01	68.0	30	8.0	10	0.4
Prosopsis cineraria leaves	2.88	0.09	0.45	0.61	0.22	562	28	4.0	62	0.1
Prosopsis cineraria stem/twigs	1.25	0.14	0.23	1.01	0.95	224	50	8.0	18	0.3
Prosopsis cineraria seeds	0.62	0.28	0.23	2.16	0.03	192	35	10.0	16	0.2
Brand A sheep pellets	1.39	0.43	0.22	1.11	0.51	713	172	40.0	59	1.1
Brand B sheep pellets	1.43	0.77	0.28	0.99	0.26	449	51	18.0	102	1.7
Gazelle pellets	1.31	0.50	0.24	1.13	0.52	1140	134	37.0	79	1.1
Mineral block A[3]	-	-	-	-	34.0	75.0	15	280	25	-
Mineral block B[3]	-	-	0.02	-	38.0	1550	310	550	210	-

[1] Yellow (sun-ripened); [2] green (on the tree); [3] manufacturer-stated composition.

Table 5. Selected nutrient composition of seven species of browse species used to feed captive ungulates at BCEAW, United Arab Emirates, compared to previously published values (in parentheses)[1]. All data presented on a dry matter (DM) basis.

	CP (%)	ADF (%)	NDF (%)	Ash (%)	Lignin (%)	Ca (%)	P (%)	Cu (mg/kg)	Zn (mg/kg)	Fe (mg/kg)
L. leucocephala leaves	23.4 (23.3)	23.9 (21.4, 25.4)	32.6 (34.9, 40.9)	9.73 (8.5)	7.9 (10.8)	0.56 (1.07)	0.33 (0.21)	8.0 (13)	31.0 (30)	150 (261)
Phoenix dactylifera leaves	5.8 (4.8)	44.7 (59.8)	48.8 (81.5)	20.03 (12.9)	14.9 (14.6)	0.96 (0.7)	0.05 (0.1)	5.0 (-)	28.0 (-)	658 (-)
A. tortilis leaves	17.3 (14.4, 18.9)	28.5 (21.5, 32.1)	30.4 (37.6, 55.1)	6.8 (11.7)	13.9 (13.7)	1.31 (3.41)	0.17 (0.15)	5.0 (39)	19.0 (12)	593 (229)
A. nilotica leaves	12 (13.7, 17.6)	20.1 (13.4, 17.0)	21.8 (22.2, 22.7)	7.95 (8.7)	7.2 (6.5)	1.91 (1.81)	0.1 (0.14)	8.0 (9)	33.0 (39)	740 (-)
Pithecelobium dulce leaves	28.4 (21.3, 23.0)	27.1 (22.9, 29.4)	37.1 (40.18, 40.2)	6.85 (8.4)	9.7 (12.3)	1.01 (3.63)	0.25 (0.14)	12.0 (-)	29.0 (-)	278 (-)
Pithecelobium dulce seeds[2]	15.9 (10.2)	22.9 (14.7)	33.6 (20.9)	5.49 (-)	7.1 (-)	0.19 (-)	0.19 (-)	8.0 (-)	23.0 (-)	86.0 (-)

[1] Data obtained from the following sources: Dzowela et al. (1997); Rubanza et al., (2004); Bhatta (2005); Kahindi et al. (2007); Olivares-Perez et al. (2011); Feedipedia (2014). [2] Yellow (sun-ripened).

adjusted CP (ACP) was determined (i.e. CP - ADICP) and the ACP was entered into the database for the relevant feedstuff (as per Rasby et al. 2008). Neutral detergent soluble fibre (NDSF) was also calculated from laboratory values (as per Kearney and Dierenfeld 2005). Intake amounts of each ingredient were then entered into Zootrition®, and diets were compared to published guidelines for daily nutrient intake in the Dorcas gazelle (Jansen and Nijboer 2003) and for medium-sized, intermediate browsing ungulates (e.g. goats, ibex, eland, springbok, Dama gazelle; Lintzenich and Ward 1997).

Statistics

When all nutrient composition data were categorised according to plant component (leaf, stem/twig or seed pod, regardless of species), they were found to be normally distributed (Kolmogorov-Smirnov test), with the exceptions of ash, Na and Mo. Nutrient comparisons of leaf, stem/twig and seed pod components for the seven browse species were completed using ANOVA (parametric data) or Kruskal-Wallis test (non-parametric data). Post-hoc tests were performed where a significant difference was detected between components, using the Bonferroni (parametric data) or Tukey HSD (non-parametric data) test. Feed intake data (parametric) were compared among species using ANOVA. A Pearson correlation analysis was performed to determine any relationship between percentage of pellets included in the diet or browse intake (g/kg BW), with percentage of gastrointestinal (GI) disease identified in the population. Statistical analyses were performed using SPSS (IBM SPSS Statistics for Windows, Version 21.0, Armonk, NY: IBM Corp). For the dietary evaluation, an arbitrary acceptable margin of difference from the published recommended daily intake (RDI) for each nutrient was set at ±20% of recommendation.

Results

Browse species and pelleted diets

Nutrient composition of the browse species (separated by plant fractions) and pelleted diets is provided in Tables 2–4, along with leaf-to-edible stem/twig ratios (Table 2). For the purposes of dietary evaluation, the edible-to-inedible fraction was also calculated (Table 2).

When evaluated regardless of species, no significant differences were detectable among plant fractions for DM, CP, NFC, crude fat, Na, Cu, Na or Mo. However, NDF was higher in stem/twig fractions ($p = 0.01$) and seed pods ($p = 0.01$) than leaves, and differences between fractions in ADF approached significance ($p = 0.06$). Neutral detergent soluble fibre was significantly higher ($p = 0.02$) in browse leaves (all species combined; 34.27±5.65%) compared to pelleted feeds (all brands combined; 9.30±0.97%). Compared to stems/twigs, leaves of all species combined were lower in Zn ($p = 0.02$), but higher in Fe ($p = 0.05$). Leaves were higher than seed pods in ash ($p = 0.01$), Ca ($p = 0.04$), Mg ($p < 0.01$), Fe ($p < 0.01$), and Mn ($p = 0.01$), but lower in P ($p = 0.04$), and K ($p < 0.01$).

Between-species variation was compared to previously published values and is presented in Table 5. Total calculated digestible nutrient content ranged from 44 to 77%, although the majority of samples were above 60% (the exceptions being *P. cineraria* stems/twigs (44%), date palm leaves (50%), and leucaena stems/twigs (52%). Acid detergent fibre ranged between 13.2 and 45%, and NDF between 21.8 and 56%. Lignin values fell between 3.7 and 23% and starch between 0.6 and 5.9%, with one sample considerably higher in starch at 13.2% (green *P. dulce* seed pods). Crude protein concentrations ranged, for the most part, between 12 and 18%, although date palm was particularly low (5.8%), whereas leucaena leaves and seeds, as well as *P. dulce* leaves, were higher than the typical range detected at 24–30%.

Calcium was highest in *P. cineraria* leaves and lowest in *P. dulce* green seed pods. Date palm leaves were relatively low in P, compared to the other samples analysed (0.1–0.33%), but all species had Ca:P ratios > 1 in all fractions, with the exception of *P. dulce* seeds (green; 0.6). Iron varied widely, ranging from 68 to 740 mg/kg DM (in *P. dulce* green seeds and *A. nilotica*, respectively). Zinc was lowest in *A. tortilis* leaves and highest in *P. cineraria* stems/twigs, whilst copper was lowest in *P. cineraria* leaves and highest in *P. dulce* leaves.

Vitamin concentrations were not determined in the current study for any dietary component. However, manufacturer-stated composition of the vitamin premix added to two brands of pellets (Brand A and Gazelle pellets) indicated that these pellets were likely to contain at least 10,000–16,400 IU/kg of vitamin A, 1000–1100 IU/kg of vitamin D_3 and approximately 50 mg/kg vitamin E. One of the sheep pellets (Brand A) was found to contain a particularly high concentration of copper (40 mg/kg DM). The iron content of the Gazelle pellet was also notably high (>1000 mg/kg DM). Mineral content of the two salt licks provided is described in Table 4.

Table 6. Determined feed intake of three species of ungulate at the BCEAW (g/kg BW). Data are expressed as mean (±SEM).

	Mean body weight (kg)[1]	Daily feed intake: browse		Daily feed intake: pellet		Ratio browse: pellet		Total DMI[2] (% of BW)
		As-fed	DMB	As-fed	DMB	As-fed	DMB	
Arabian mountain gazelle *Gazella g. cora* (n=30)	9.46 (0.35)	11.10 (1.44)	3.91 (1.13)	35.24 (3.22)	32.14 (0.53)	0.31	0.12	2.82
Dorcas gazelle *Gazella g. dorcas* (n=27)	11.68 (0.59)	11.41 (0.40)	4.02 (0.49)	38.05 (0.00)	34.70 (0.00)	0.30	0.12	3.87
Arabian tahr *Hemitragus jayakari* (n=2)	17.5 (0.90)	16.10 (1.11)	5.67 (0.88)	3.65 (0.34)	3.32 (0.31)	4.42	1.70	0.9

[1]Measured within 4 months of the study; [2]dry matter intake.

Feed intake

Feed intake (FI; % BW) for the three species assessed is shown in Table 6. When compared on a metabolic body weight basis (MBW; $BW^{0.75}$), no difference in FI was detectable between the Arabian gazelle and Dorcas gazelle, but both species' FI were found to differ significantly from the Arabian tahr FI ($p < 0.01$) for both browse and pellets (analysed separately). Subsequently, dietary intake calculations were restricted to these three species, and no extrapolation was made to other species housed at the BCEAW. Dry matter intake (DMI) ranged from less than 1% of body weight (tahr) to almost 4% (Dorcas gazelle).

Palatability of each browse species was not determined in this study.

Table 7. Calculated nutrient composition (on a dry matter basis) of three diets fed to captive ungulates at the BCEAW, UAE.[1]

	Arabian gazelle	Arabian tahr	Dorcas gazelle
Metabolisable energy[2] (kJ/kg)	10418	11339	10418
ADF (%)	23.26	21.16	23.24
NDF (%)	35.76	33.08	35.75
NFC (%)	37.09	36.05	37.14
Crude Fat (%)	2.93	5.06	2.92
Crude Protein (%)	16.80	22.04	16.74
Ash (%)	11.18	7.48	11.20
Calcium (%)	1.28	1.18	1.28
Copper (mg/kg)	34.31	13.60	34.42
Iron (mg/kg)	1,047.12	332.58	1,051.08
Magnesium (%)	0.25	0.29	0.25
Manganese (mg/kg)	73.29	52.28	73.53
Molybdenum (mg/kg)	1.00	0.72	1.01
Phosphorus (%)	0.47	0.42	0.47
Potassium (%)	1.18	1.38	1.18
Sodium (%)	0.47	0.11	0.47
Zinc (mg/kg)	122.69	36.07	123.17

[1]As calculated in Zootrition® using laboratory-determined analytical values for all browse and pellet feedstuffs, as well as Zootrition® values for carrots and apples (Arabian tahr only). [2] Calculated using NRC (2001) equation for dairy cattle.

Diet composition

For the three species for which accurate feed intake records are available, the daily nutrient intakes are provided in Table 7. Browse (*P. dulce*) contributed approximately 11.5% of ME for Arabian gazelle and Dorcas gazelle, respectively, but 60.0% for Arabian tahr (*P. dulce*, *P. cineraria*, *Z. spina-christi* and hay). Calculated ME (using the NRC (2001) equation for dairy cattle) was similar across diets. Acid detergent fibre and NDF were also similar among the three diets (Table 7) and met or exceeded the NDF RDI (27.45% NDF using the intermediate-browser RDI, or 33.80% NDF using the Dorcas gazelle RDI, both on a DM basis). Calculated neutral detergent soluble fibre (NDSF) for the three diets (using the sum of proportional contributions of browse and pellets and calculated NDSF for each component) was highest in the Arabian tahr diet (17.54%), compared to 9.20% and 9.07% in the Arabian gazelle and Dorcas gazelle diets, respectively. Crude fat and CP were both higher in the Arabian tahr diet compared to the other two diets (Table 7), and in the case of CP, the Arabian tahr diet was found to exceed the RDI (15.30% intermediate-browser RDI, or 18.90% using the Dorcas gazelle RDI).

Vitamin A content in the Arabian tahr diet was calculated using data from the produce (2.3% of ingredients; carrots and apples) as well as the estimated pellet content, whilst the Arabian gazelle and Dorcas gazelle dietary vitamin A was calculated using only data from the pellets. The calculated minimum total dietary vitamin A concentration was approximately 12.0 IU/g for the Arabian tahr diet, which is 6.9–8.3 times higher than the RDI. Similarly, the Arabian gazelle and Dorcas gazelle diets were predicted to provide at least 9.0 IU/g vitamin A (5.6–5.7 times the RDI of vitamin A). Estimated minimum vitamin D_3 concentration in the Arabian gazelle and Dorcas gazelle diets were 0.89 IU/g (compared to the RDI of 0.41 IU/g), whereas the Arabian tahr diet contained about half that concentration (0.39 IU/g). The minimum vitamin E content of all three diets (44.6, 44.8, and 20.7 IU/g in the Arabain gazelle, Dorcas gazelle and Arabian tahr diets, respectively) was lower than the RDI (113.4 IU/g).

Ash content of the Arabian gazelle and Arabian tahr diets was 11.2%, whereas the Dorcas gazelle diet provided less (7.5%). Dietary mineral concentrations compared to the RDIs are provided in Figures 1 and 2. All diets achieved a Ca:P ratio similar to that recommended for intermediate browsers (2.7–2.8; compared to the RDI of 2.85), although ratios were higher than that reported for the Dorcas gazelle RDI (1.63). With the exception of Na and Zn in the tahr diet, other macro- and trace mineral concentrations met or exceeded RDIs.

Post-mortem findings

Digestive disturbances were most commonly diagnosed in sand gazelles (4.17% occurrence). Following this, 2.13% of Nubian

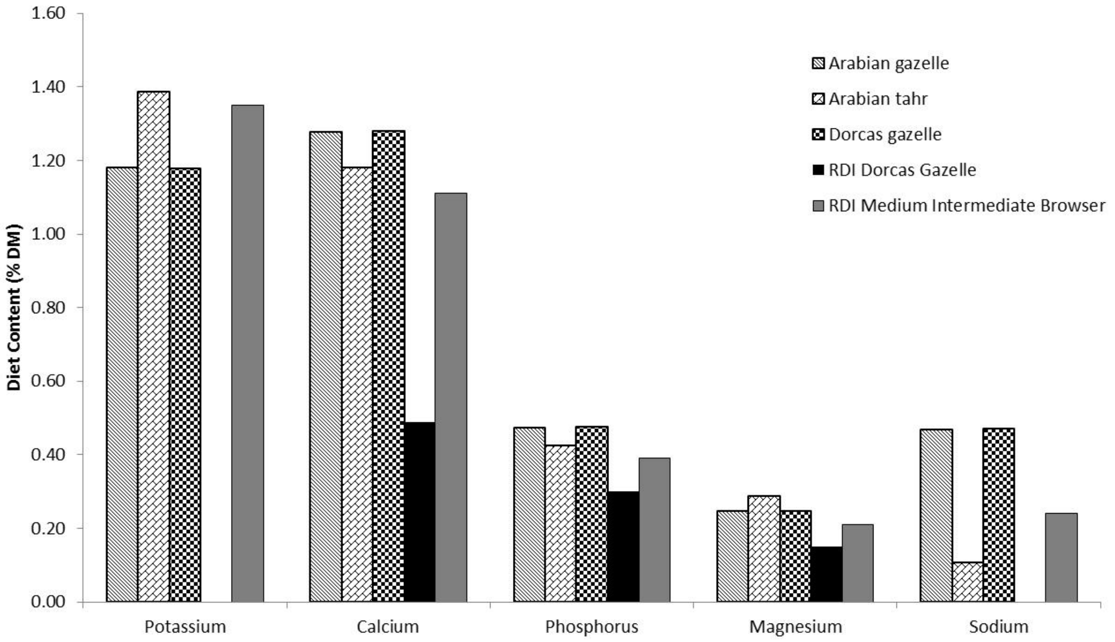

Figure 1. Calculated daily intake of potassium, calcium, phosphorus, magnesium and sodium provided by a mixed diet of browse and commercial pelleted feed for three species of ungulate (Arabian mountain gazelle, Arabian tahr, and Dorcas gazelle) at the BCEAW (UAE), compared to the recommended daily intake (RDI) for Dorcas gazelle (Jansen and Nijboer 2003), or for medium-sized intermediate-browsers (Lintzenich and Ward 1997).

ibex, 1.35% of Arabian oryx and 0.57% of Arabian mountain gazelle necropsied had GI disease identified. No cases of digestive disturbance were detected in necropsied Arabian tahr. Figure 3 illustrates the differences between incidences of GI disease findings on post-mortem between the current and a previous study (tahr not shown but Gattiker et al. (2014) also reported 0% incidence in the Himalayan tahr, a related species). Data for Dorcas gazelle were not available.

Proportional use of pelleted feeds and browse offered in the diet of ungulates included in this study was compared to that reported by Gattiker et al. (2014); the findings are described in Figures 4 and 5, respectively.

Gattiker et al. (2014) previously reported a relationship between the percentage of unstructured feed items (pellets and produce) in the diet, with the proportion of GI disease. To evaluate the potential for a similar relationship in the current study, two

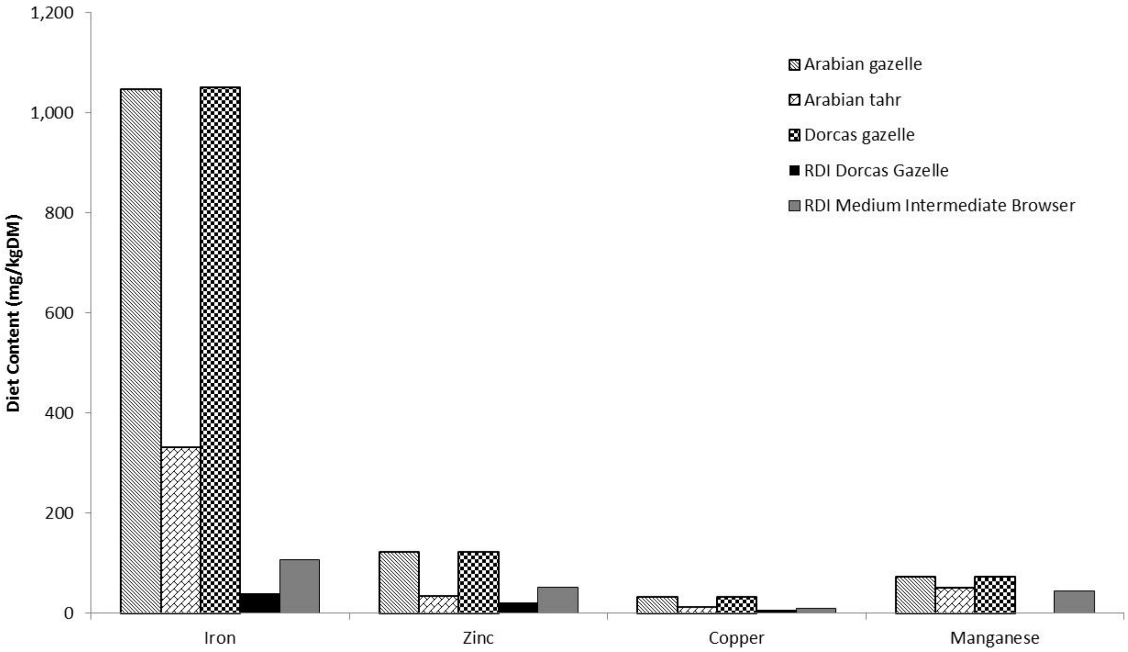

Figure 2. Calculated daily intake of iron, zinc, copper and manganese provided by a mixed diet of browse and commercial pelleted feed for three species of ungulate (Arabian mountain gazelle, Arabian tahr, and Dorcas gazelle) at the BCEAW (UAE), compared to the recommended daily intake (RDI) for Dorcas gazelle (Jansen and Nijboer 2003), or for medium-sized intermediate-browsers (Lintzenich and Ward 1997).

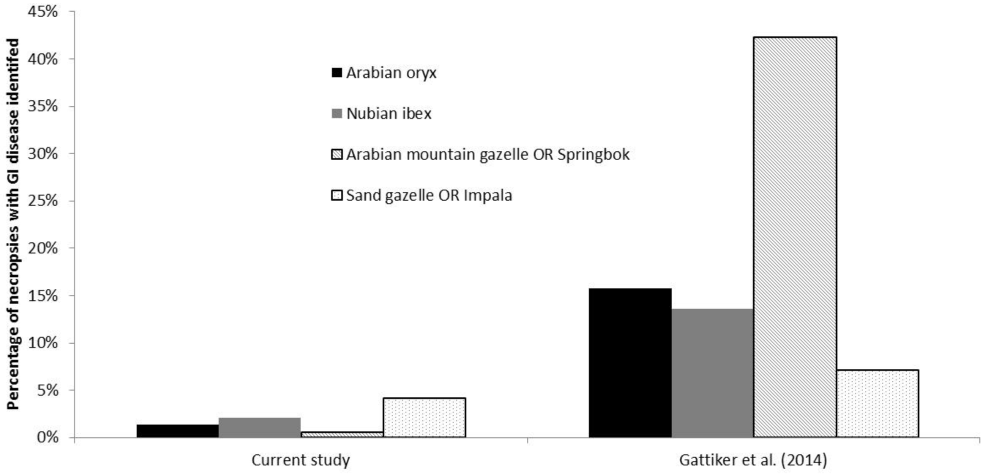

Figure 3. Comparison of proportion of necropsied ungulate species with digestive disturbance (current study) or ruminal acidosis, rumenitis and/or parakeratosis (Gattiker et al. 2014). Information for Arabian mountain gazelles (current study) was compared to springbok data (Gattiker et al. 2014), whilst sand gazelles (current study) were compared to impala (Gattiker et al. 2014).

Pearson correlations were performed, but failed to achieve statistical significance for either proportion of pellets ($R^2 = {}^{-}0.28$, $p > 0.05$) or browse intake ($R^2 = 0.5$, $p > 0.05$).

Discussion

Browse species

The nutritional composition of seven species of browse, cultivated locally in the UAE, was determined and compared to previously published values for each species. Our findings indicate that, overall, only moderate variation exists within species composition when grown in an arid environment (i.e. the current study), compared to tropical or sub-tropical environments (previous reports, see Table 6). However, some exceptions to this were identified, including *Acacia tortilis* containing lower than predicted Ca and Cu levels, but higher than expected Fe. Relative to the other browses analysed here, *A. nilotica* was also found to be particularly high in Fe as well as Na; the latter result is not typical of acacias in general (no comparative data on this particular species was available). Likewise, the high Ca:P ratio (4.4) determined in seed pods of this species is unusual given that the reproductive fractions of plants are typically higher in P than Ca; inclusion of pod tissues (in addition to seeds) probably influenced the mineral content of the samples analysed here. Since this component was analysed in the form consumed by animals, this finding is of particular interest given the favourable Ca:P ratio compared to what may have been predicted from published literature (and seed) alone.

Soil type, particularly its nutrient status, as well as local growing climate, are known to influence plant nutrient content, especially in regard to mineral composition (Bauer et al. 1997). However, no

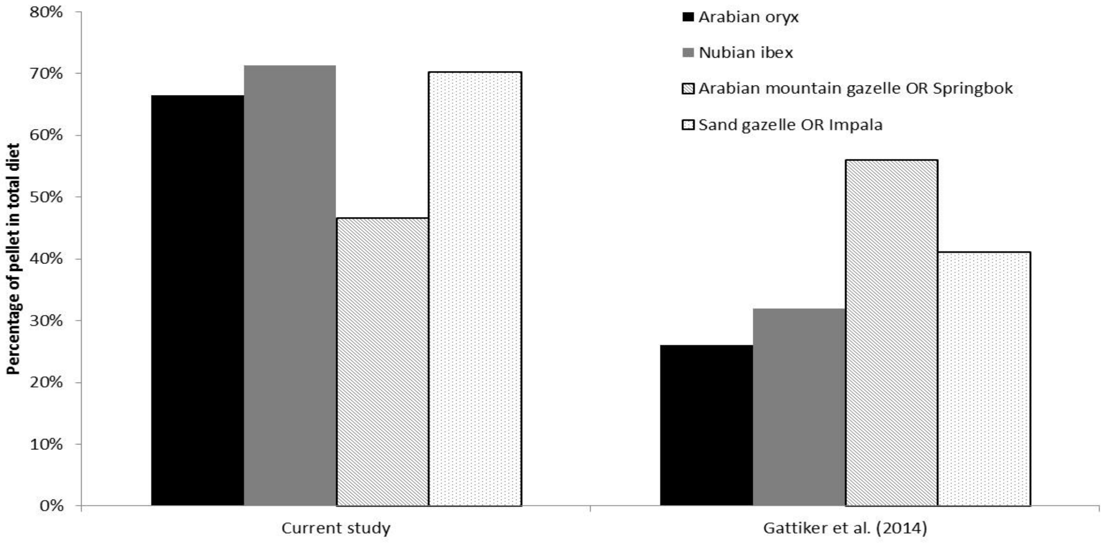

Figure 4. Comparison of proportion of pelleted feedstuff offered to captive ungulates at the BCEAW (UAE; current study) and the National Zoological Gardens (South Africa; Gattiker et al. 2014). Information for Arabian mountain gazelles (current study) was compared to springbok (Antidorcas marsupialis) data (Gattiker et al. 2014), whilst sand gazelles (current study) were compared to impala (Gattiker et al. 2014).

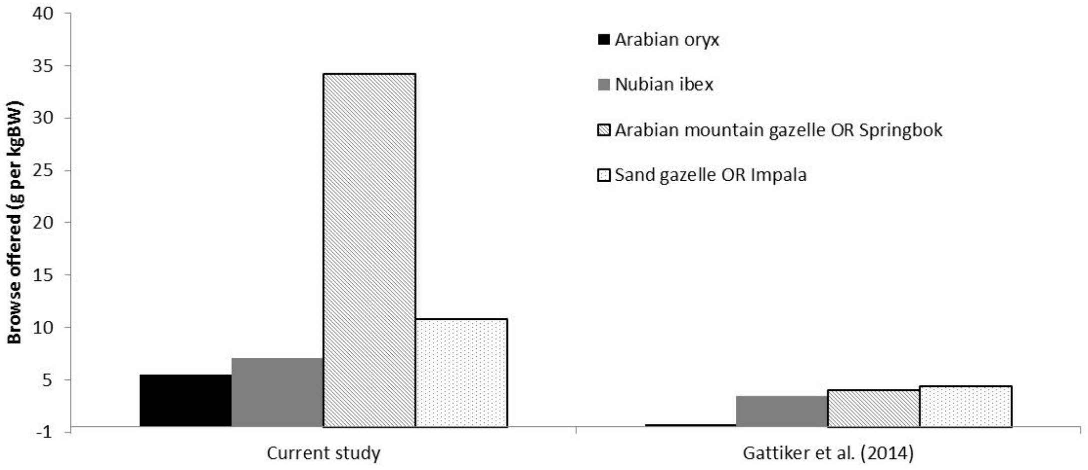

Figure 5. Comparison of the quantity of browse feedstuff (g/kg BW) offered to captive ungulates at the BCEAW (UAE; current study) and the National Zoological Gardens (South Africa; Gattiker et al. 2014). Information for Arabian mountain gazelles (current study) was compared to springbok (Antidorcas marsupialis) data (Gattiker et al. 2014), whilst sand gazelles (current study) were compared to impala (Gattiker et al. 2014). Note: Arabian oryx were not offered any browse in the Gattiker et al. (2014) study so the y-axis of this figure includes negative values in order to represent the zero value for this species.

pattern indicative of an environmental influence could be detected in the differences observed between mineral content of browses analysed in the current study compared to previous publications. In this regard, it must be acknowledged that the browse species selected for analysis here were obtained from within the Sharjah Desert Park, where artificial irrigation systems are in operation. As such, the samples analysed represent cultivated forms of each browse species. Lastly, soil contamination of samples was ruled out as a potential cause of the higher than expected Mn in ghaf tree and Fe in *Z. spina-christi* since neither are low-growing plants and samples were obtained from aerial branches. However, the higher than expected Fe content of the two *Acacia* species and *Z. spina-christi*, along with high levels seen in date palm (*P. dactylifera*), may be associated with the high iron oxide content of sand dunes (FAO 1985), which form the predominant soil type in the area (EAAD 2012).

As expected, the browse species evaluated here were considerably higher in fibre but lower in starch than the pelleted feeds. Even the particularly high starch content of the green *P. dulce* seed pods was only about half that of the pelleted diets. Starch is positively correlated with the acidogenicity value (AV) of a ruminant feed, whereby higher AVs and/or starch contents are indicative of reduced rumen function and increased risk of ruminal acidosis (Odongo et al. 2006; Clauss and Dierenfeld 2008). The starch content of pelleted diets (22–29%) approached the maximum recommended threshold (30%; Odongo et al. 2006), whilst the majority of browses were below 1%. This indicates that pelleted feedstuffs should be offered only in reduced quantities, in order to avoid gastrointestinal disturbance in browsers. On the other hand, NDF was similar to the values reported for temperate browse leaves in a review by Clauss and Dierenfeld (2008) and were aligned to the RDI for intermediate-browsers (Lintzenich and Ward 1997).

Relative to the browse species evaluated here, high Ca levels were detected in leucaena, *Z. spini-christi*, and ghaf leaves, and are suspected to represent high oxalate inclusion, typical of desert species (Brown et al. 2013). Hence, the Ca level in these species may not represent Ca that is as bioavailable as that in other species/forms due to the binding activity of oxalates (Noonan et al. 1999), but this remains to be investigated.

Nutrient composition also varied within species according to the plant fraction sampled. For example, seed pods (in general) may be poor sources of Mg, Mn and Ca (with the exception of *A. nilotica*), whilst leaves were typically higher in Fe than both stem/twigs or seed pods. The variation observed may reflect mineral partitioning within the plant and supports our use of leaf:stem/twig ratios to calculate proportional inclusion of each component during total dietary intake evaluation.

Neutral detergent fibre content was higher in stem/twig fractions than leaves or seed pods, reflecting the high contribution of structural constituents such as lignin, hemicellulose and cellulose to this browse fraction. This was supported by the higher lignin concentrations determined in stems/twigs compared to leaves. When formulating diets for species known to consume woody plant fractions, the decreased digestibility of such ingredients with elevated lignin content should be taken into consideration (Hummel et al. 2006; Clauss and Dierenfeld 2008).

As a crude estimate of tannin content, the high ADICP value (>10%) detected in at least one fraction from each species suggest that tannins may be an important factor in these browses. The forage database, Feedipedia, provides support for this: the tannin contents of leucaena and *A. nilotica* leaves are reported as 27.6 g/kg DM and 13.0 g/kg DM condensed tannin (CT), or 23.8 g/kg DM and 48.7 g/kg DM tannic acid (TA), respectively. Likewise, *A. tortilis* leaves are reported as containing 2.3 g CT/kg DM or 60.2 g TA/kg DM (Feedipedia 2014). The inclusion of dietary tannins may assist with rumen bypass protein, improve feed conversion, act as a parasiticide, and/or be of value in binding excess Fe (Spelman et al. 1989; Clauss et al. 2003b, 2007; Lisonbee et al. 2009), the latter of which may be important in light of the high Fe found in many of the browses analysed. Excess dietary iron is also known to interfere with absorption of other minerals, such as Cu. However, dietary tannin intake can also induce negative physiological changes. In domestic ruminants, a condensed tannin intake of more than 50 g/kg DM has been shown to reduce voluntary food intake, impair digestive utilisation of forages and reduce body weight gain in growing animals (Frutos et al. 2004; Ladipo and Akinfemi 2014). In light of these findings, the moderate tannin concentrations (24–60 gTA/kg DM and 2–28 gCT/kg DM) reported in leucaena, *A. tortilis* and *A. nilotica* (Feedipedia 2014) may be either harmless or perhaps even beneficial, given that they are provided as only a minor component of the total diet at the BCEAW. In contrast, the species that forms the staple browse component for ungulates at the BCEAW (*P. dulce*) is reported to contain only 0.1 g CT/kg DM and 2.8 gTA/kg DM (Feedipedia 2014), which is unlikely to have any counteracting influence on the high Fe content of the total diet. Consequently, it may be prudent to consider revising the diet to either reduce the iron content (mainly from pellets), or increase the intake of dietary tannins, perhaps by increasing the utilisation of high tannin browses.

Complete diets

In comparison to published RDIs for captive browsers, none of the three diets assessed was found to be deficient in the nutrients evaluated. However, some noteworthy differences between the gazelle (both Arabian and Dorcas gazelle) and Arabian tahr diets were detected, whereby the Arabian tahr diet was generally more closely aligned to the RDIs for all available nutrients, whilst the two gazelle diets tended to oversupply certain nutrients.

The low utilisation of browse in the two gazelle diets renders them particularly reliant on the pelleted component of their diet, which is contrary to recommendations towards a greater inclusion of browse (Clauss et al. 2003a; Clauss and Dierenfeld 2008). Lintzenich and Ward (1997) recommend pellets comprise no more than 30–40% of the diet (on an as-fed basis), whereas our two gazelle diets greatly exceeded this (>75% intake, as fed). Based on relative starch contributions from pellets and *P. dulce* browse, the starch content of the complete diets could be predicted to be about 21% for the two gazelle diets at the BCEAW. In contrast, the Arabian tahr diet was predicted to provide only 7% starch due to the much greater utilisation of browse and minimal quantities of pelleted feedstuff. Browse fermentation results in high concentrations of energy-yielding acetate, in the absence of the detrimental end-product lactate (as discussed in Kearney and Dierenfeld 2005). In contrast, high levels of dietary starch or sugars (which are also rapidly fermented but lead to lactic acid end products) have a higher potential to negatively alter the rumen pH and microbial populations, decrease the type and number of cellulotyic bacterial species, further slow the plant degradataion process (Russell and Rychlik 2001; Clauss and Dierenfeld 2008); detrimental effects have been observed in deer consuming 12–24% starch (Koutsos 2009; McCusker et al. 2011). The estimated 21% starch provided in the diet of the two gazelle species evaluated here indicates dietary modification may be necessary.

Nonetheless, NDF and ADF concentrations were similar among all three diets and were reasonably well aligned to recommended RDIs. However, the Arabian tahr diet was found to greatly exceed the RDI for protein, which may be, at best, unnecessary, or even potentially detrimental (Clauss and Dierenfeld 2008). The majority of protein (71%) was calculated to be provided by the high proportion of *P. dulce* used in this diet, and a slight reduction in *P. dulce* may better balance the diet overall. Rumen microbes provide the primary nitrogen (protein) supply to ruminants, with a minimal requirement of about 7% of dietary DM (Clauss et al. 2003a); based on this diet assessment, increased reliance on mixed browse species may be suitable for all herbivores at BCEAW. Likewise, the high vitamin A, low fibre and high starch/sugar content calculated from the fruit and vegetable component of the Arabian tahr diet indicate that these components may be wasteful and their exclusion is unlikely to be detrimental for this species.

Despite apparently suitable NDF values, both the amount (quantity) and quality (type) of CHOs must be considered in the diets fed to herbivores, as both have interacting consequences for intake, processing and utilisation. Calculated NDSF concentrations in the browse species and pellets evaluated here were similar to those previously reported for alfalfa hay and two brands of concentrates fed to zoo browsers analysed by Kearney and Dierenfeld (2005). However, when this information was extrapolated to the complete diets fed at BCEAW, the NDSF concentrations of the Arabian and Dorcas' gazelle diets were especially low (9.1–9.2%). These diets were estimated to provide no greater NDSF than if the animals were consuming a diet consisting solely of pelleted feedstuffs (6.9–10.6%; Kearney and Dierenfeld 2005; current study). In contrast, the Arabian tahr diet contained a higher NDSF fraction (17.5%), which more closely resembled that of alfalfa hay (15.2%; Kearney and Dierenfeld 2005), but was still considerably lower than the average NDSF of browse (34.3%; current study). Neutral detergent soluble fibre represents pectic substances found as part of the non-fibre carbohydrate fraction and, when fed in large proportions relative to starch and sugar, has been shown to promote improved digestive parameters in domestic ruminants (as discussed in Kearney and Dierenfeld 2005). Combined, these findings support a recommendation to increase the utilisation of browse components, and reduce the relative contribution of pelleted feeds, for ungulates at the BCEAW.

Nonetheless, comparison between our collection and the data reported by Gattiker et al. (2014) indicates that digestive-related post-mortem findings are relatively low in the BCEAW ungulates. Gattiker et al. (2014) determined a significant correlation between the proportion of unstructured (pellets and produce) feed items in the diet and the percentage of ruminal acidosis, rumenitis and/or parakeratosis detected. Although no such relationship was detectable in the current study, the reason for the relatively low incidence of digestive disturbances reported for the BCEAW collection deserves further mention. Whilst it is feasible that non-dietary related husbandry factors are involved, the amount of browse reported as offered to similar ungulates in the facility investigated by Gattiker et al. (2014) was notably lower than offered at the BCEAW. Moreover, when considering NDSF intake using determined feed intake data for the three species evaluated here, the nearly double NDSF concentration of the Arabian tahr diet compared to the gazelle species may provide partial explanation for the absence of digestive disorders observed in this species, in comparison to the 1–4% incidence observed in species with lower NDSF intake. Further research is required to investigate this hypothesis.

Calcium and phosphorus intakes were within the range of RDIs reported, as was the calculated Ca:P ratio for all three diets. However, Na varied considerably between the gazelle and tahr diets, with the former providing excess and the latter appearing relatively deficient in this nutrient. The provision of a salt lick for the Arabian tahr is likely to address this Na deficiency, although it would be advisable to replace the current product with a non-mineralised block, in light of the already adequate or excessive dietary mineral intake determined here. Of particular concern was the excessive Fe concentration detected in all three diets. The reason for the particularly high Fe content of one of the pelleted diets is currently being investigated in collaboration with the manufacturer. In the two gazelle diets, the predicted content exceeded the maximum tolerable concentration of 1000 mg/kg reported for cattle (NRC 2000). Iron toxicity in cattle is associated with copper deficiency but can also cause gastrointestinal disturbances and metabolic acidosis (NRC 2000), and dietary modification is therefore advisable at the BCEAW.

Zinc and copper were both provided in excess of RDIs but calculated Zn:Cu ratios were within an acceptable range (4:1), suggesting that the Zn levels provided here are unlikely to be harmful. Copper concentrations in the range of 40.7 (±32.6) mg/kg up to 58.9 (±36.7) mg/kg Cu were associated with deaths in free-ranging impala (*Aepyceros melampus*; Grobler 1999). The two gazelle diets evaluated in the current study had a predicted Cu content of 34 mg/kg, which is within one standard deviation of the concentrations reported by Grobler (1999). Precautionary dietary modification would therefore seem judicious, and reduced use of the commercially-prepared pellet (with a mean contribution of 96% of the Cu consumed) is recommended to improve overall mineral balance in the gazelle diets. Consultation with the manufacturer of the pelleted diets is on-going, and a subsequent batch has been shown to contain markedly lower Cu concentrations. This further highlights the importance of quality control systems within zoo kitchens in order to identify and control for any noteworthy inter-batch variation in ingredient composition that is likely to influence total dietary provision.

In reviewing the findings of this study it is important to acknowledge that specific nutrient requirements for the species housed at the BCEAW have not been established. Therefore, reliance was placed on recommendations based on requirements for domestic species (Jansen and Nijboer 2003), or extrapolated from literature in free-ranging related species (Lintzenich and Ward 1997). As such, the dietary evaluation conducted here should be interpreted with caution, particularly since animal health status was not monitored in conjunction with dietary intake but was instead based on historical data collected for other purposes. Likewise, seasonal variation in nutrient composition of browses was not assessed, and accurate feed intake data were not available for all species housed at the BCEAW. Nonetheless, key areas of potential improvement have been identified for all three diets evaluated and predictions can be made for other species fed similar diets at the BCEAW. Moreover, the data generated in the current study should be of particular value to zoo nutritionists working in the Arabian Peninsula, and potentially elsewhere in the world, when formulating ungulate diets based on regionally-available browse species.

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