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Nutrition of goats, sheep and cattle in tropical and warm conditions “ Evaluation of energy and protein requirements and animal responses to diet. Evaluation of INRA system to predict nutritive value of forage resources ”

Nizar Salah

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Alimentation de caprins, ovins et bovins viande dans les régions chaudes

Évaluation des besoins énergétiques et protéiques des animaux et réponses animales à l'alimentation

Évaluation du système d'unité d'alimentation INRA à prédire la valeur des ressources fourragères

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Co-encadrement de la thèse : **Daniel SAUVANT**

Jury

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LISTE DES ABBRÉVIATIONS

ADF: Acid Detergent Fiber

ADG: Average Daily Gain

ARC: Agricultural Research Council

CP: Crude Protein

CSIRO: Commonwealth Scientific and Industrial Research Organization

DCP : Digestible Crude Protein

DE: Digestible Energy

DMI: Dry Matter Intake

ECH₄: Energy in methane

ED_N: Effective Degradability of nitrogen

FAO: Food and Agriculture Organization on the United Nations

FN: Fecal Nitrogen

GE: Gross Energy

INRA : Institut National de la Recherche Agronomique

LW: Live Weight

ME: Metabolizable Energy

MEC: Metabolizable Energy Concentration

MEI: Metabolizable Energy Intake

MLW, LW^{0.75}: Metabolic Live Weight

MP: Metabolizable Protein

NDF: Neutral Detergent Fiber

NE: Net Energy

NRC: National Research Council

OMd: Organic Matter Digestibility

OMI: Organic Matter Intake

PDI: Protein Digestible in the Intestine

RN: Retained Nitrogen

RSD: Residual Standard Deviation.

SR: Small Ruminant

UE: Urinary Energy

UF: Unité Fourragère

UN: Urinary Nitrogen

URZ: Unité de Recherches Zootechniques

Nmic: Azote microbien

NDFD_{int}: Neutral Detergent Fiber Digested in the intestine

MOF: Fermented Organic Matter

drN: true digestibility of protein in the intestine

GES : Gaz à effet de serre

RESUMÉ

L'objectif général du projet de thèse était de produire des connaissances pour contribuer au développement de bonnes pratiques d'alimentation des caprins, ovins et bovins des régions chaudes. La méthodologie utilisée dans ce projet a croisé des méta-analyses à une approche expérimentale. Les besoins énergétiques d'entretien des caprins, ovins et bovins des régions chaudes seraient plus élevés que ceux des ruminants des régions tempérées. Ces différences ont été partiellement attribuées à la capacité des génotypes animaux de ces régions de mobiliser une fraction des nutriments ingérés à des fonctions non productives dont l'adaptation aux stress et le coût énergétique de l'ingestion et la digestion de rations plus fibreuses. Des besoins énergétiques pour la production du même ordre de grandeur que ceux des génotypes des régions tempérées ont été estimés. Nos estimations des besoins protéiques d'entretien et de production indiquent que ceux-ci sont plus élevés avec les génotypes tropicaux comparativement aux génotypes tempérés.

La hiérarchie des besoins entre espèces varie avec leurs modalités d'expressions (expression du poids métabolique).

Le système d'unité d'alimentation énergétique et protéique de l'INRA, basé sur une approche mécaniste de l'utilisation des aliments, conduit potentiellement à une bonne évaluation des ressources alimentaires. Cependant, certains coefficients doivent être révisés pour tenir compte de la composition spécifique des ressources fourragères disponibles en régions chaudes.

Mot clés : *Méta-analyses, ovins, caprins, bovins, régions chaudes, croissance, digestibilité, ingestion.*

ABSTRACT

The overall aim of the thesis project was to generate knowledge to contribute to the development of good feeding practices for sheep goats and cattle in warm regions. The methodology used in this project crossed meta-analysis to an experimental approach. The maintenance energy requirements of goats, sheep and cattle in warm regions are higher than those of ruminants in temperate regions. These differences were partly attributed to the capacity of livestock genotypes of these regions to mobilize a fraction of the nutrients ingested for unproductive functions adaptation to stress and the energy cost of ingestion and digestion of more fibrous diets. The estimation for the energy requirements for production was the same order of magnitude as the genotypes of temperate regions. Our estimates of protein requirements for maintenance and production show that they are higher with tropical genotypes compared to temperate genotypes.

The hierarchy of needs between species varies with their modes of expression (expression of metabolic weight).

The energy and protein supply unit system of INRA, based on a mechanistic approach to the use of feed, potentially leads to a good assessment of food resources. However, some factors must be revised to reflect the specific composition of forage resources in warm regions.

Keywords: *Meta-analysis, sheep, goats, cattle, warm climates, growth, digestibility, intake.*

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CHAPITRE 1
INTRODUCTION GÉNÉRALE

1. Contexte général

Les projections de la FAO indiquent que la planète devra nourrir 9 milliards de personnes en 2050, ce qui constitue un important défi pour l'agriculture mondiale (FAO, 2009). L'augmentation de la demande de produits agricoles s'accompagne aussi de changements dans les habitudes alimentaires. Ainsi, entre 1967 et 2007, la consommation de viande (porc, bœuf, buffle, moutons, chèvre) a augmenté de 93 à 369% en fonction du produit considéré (FAO, 2011). L'augmentation de la production de viande de ruminant a été inférieure à 150% alors qu'elle était supérieure à 185% pour celle des monogastriques. C'est en partie, le résultat des politiques publiques des dernières décennies, qui ont identifié les monogastriques comme des espèces animales permettant d'accroître le plus rapidement la production.

L'optimisation de l'offre de produits animaux a fait appel à différentes sciences (nutrition, reproduction, génétique, santé...) qui doivent être intégrées dans un système d'élevage. Cette optimisation doit par ailleurs être intégrée à une approche plus globale du système d'alimentation humaine combinant à la fois les cultures et l'élevage, car l'offre en protéines ne se limite pas uniquement aux produits animaux. Les produits végétaux, notamment les légumineuses, peuvent y contribuer de façon significative. Les récoltes des plantes alimentaires destinées à l'homme s'accompagnent de coproduits pouvant potentiellement contribuer à l'alimentation animale. À titre d'illustration, dans les pays en développement, certaines cultures comme le maïs, le blé, le sorgho et le millet ont un double objectif : leur grain fournit de la nourriture pour les humains alors que leurs résidus fibreux sont utilisés comme aliments pour le bétail (Herrero et al, 2010). Traditionnellement, ces cultures ont été sélectionnées pour améliorer le rendement en grains, pour résister à la sécheresse et lutter contre les ravageurs. Cependant, pour conforter le double usage de ces cultures vivrières dans les systèmes mixtes agriculture-élevage, certains programmes d'amélioration génétique ont été adaptés au cours de la dernière décennie. La qualité des résidus comme aliment pour l'élevage a été ajoutée aux objectifs initiaux d'augmentation du rendement des céréales.

Les contraintes de plus en plus fortes sur le foncier agricole conduisent aussi à reconsidérer l'usage des terres. L'impact des productions animales sur les surfaces agricoles est très variable. À titre d'illustration, pour produire 1 kg de viande, les surfaces nécessaires en m² sont respectivement de 15 à 45 pour le bœuf, 6 à 8 pour le porc et 5 à 7 pour les volailles (Hermansen et al, 2013).

Cette variabilité s'explique à la fois par la diversité des systèmes d'élevage, les rendements agronomiques des ressources produites, et la nature des aliments consommés par les animaux d'élevage. Les monogastriques présents pour l'essentiel dans des ateliers semi-industriels à industriels, souvent alimentés avec des ressources peu fibreuses et en général plus équilibrées et en concurrence avec les mêmes niches alimentaires, impactent moins l'occupation du foncier. À l'opposé, les ruminants occupent des niches alimentaires plus diversifiées. Ils peuvent aussi valoriser de nombreux coproduits de cultures et/ou s'alimenter à partir de surfaces impropres aux cultures classiques. Ces spécificités des ruminants leur confèrent une place clé dans le contexte du développement de l'agro-écologie en élevage pour répondre au challenge de l'augmentation de la production de viande.

La réduction des impacts environnementaux négatifs de l'élevage, dont la production de gaz à effet de serre (GES), est un autre défi à relever pour les prochaines décennies. Le méthane (CH_4) et certaines formes d'azote (N_2O) sont deux importants GES issus de l'activité agricole. Le CH_4 provient majoritairement de la digestion entérique (chez les herbivores notamment) et des fermentations dans les fumiers. La principale source de N_2O est l'activité des microorganismes du sol qui transforment les différentes formes d'apport d'azote (engrais minéral et organique, déjections urinaires et fécales). Certaines stratégies alimentaires permettent de réduire l'émission de certains GES tels que le méthane (Beauchemin, 2009 ; Blaxter, 1964). L'excrétion de l'azote (fécal et urinaire) et la volatilisation d'une fraction plus ou moins grande, contribuent aussi aux émissions de GES. Une plus grande adéquation tant quantitative que qualitative avec les besoins en protéines des animaux est aussi un levier pour réduire cette source de GES (Tamminga, 1992). La fermentescibilité des protéines ingérées qui contribue au pool d'azote urinaire est aussi très variable. Les excréments d'azote peuvent cependant être gérés à l'échelle de l'exploitation agricole.

L'un des moyens pour contribuer à ce défi, sans augmenter les surfaces consacrées à l'élevage est le développement de bonnes pratiques en alimentation notamment dans le milieu tropical. Ces bonnes pratiques d'alimentation vont conditionner le coefficient de transformation ou le taux de conversion des biomasses végétales en viande (kg ingéré/kg GMQ). Le National Research Council, NRC (2000) indiquait que ce coefficient variait de moins de 5 à plus de 20 kg de matière sèche (MS) ingérée par kg de GMQ chez le bovin. Chez les ovins, ce coefficient est aussi très variable : 4 à 5 kg de MS pour les rations riches en concentré (Knott et al., 2003 ; NRC, 2007), 5 à 6 kg de MS pour des fourrages de très bonne qualité (Fahmy et al., 1992), 40 kg de MS pour les pailles (Cronjé et al., 1990). Ce coefficient est d'autant plus

faible que l'aliment ingéré est digestible et que sa composition en nutriments est proche des besoins d'entretien et de production des animaux.

Les bonnes pratiques d'alimentation doivent donc être adaptées aux nouveaux défis de la nouvelle décennie et permettre de concilier l'augmentation de production à la réduction des impacts environnementaux négatifs. Historiquement, les bonnes pratiques d'alimentation se sont développées avec la conception des systèmes d'alimentation basés sur l'évaluation des besoins des animaux et la valeur des aliments. De nombreux systèmes ont été développés par différentes équipes dans le monde : en Angleterre, par Agricultural Research Council (ARC, 1980), aux USA, par National Research Council (NRC, 1985) ou dans les pays Scandinaves (Madsen, 1985). Ces systèmes ont été conçus à partir de connaissances acquises avec du matériel végétal et animal issu des régions tempérées. À notre connaissance, bien qu'utilisés pour évaluer des ressources végétales et animales des régions chaudes, ces systèmes n'ont jamais été validés avec le matériel biologique issu de ces régions. Ces systèmes ont par ailleurs été construits pour maximiser les performances permises par le potentiel génétique des animaux. Ces objectifs doivent être ajustés en intégrant les attentes de la lutte contre le réchauffement climatique et l'agro-écologie qui préconisent que la valorisation des ressources végétales et animales s'oriente vers une optimisation des fonctions productives et non-productives dans le cadre des systèmes d'élevage (Archimède et al, 2014).

2. Objectifs et démarches utilisées

L'objectif général de ce projet de thèse est d'actualiser l'information disponible pour mieux nourrir les ruminants d'élevage en régions chaudes. Plus précisément, il s'agira : 1) d'une part de préciser, dans le contexte des régions chaudes, les besoins énergétiques et protéiques des caprins, ovins et bovins en croissance ; 2) d'autre part d'évaluer l'adéquation du système d'unité d'alimentation de l'INRA pour prédire la valeur des fourrages des régions chaudes. Ce projet est une contribution au projet « SYSTALI » conduit par l'INRA qui vise à l'actualisation des systèmes d'alimentation des ruminants d'élevage.

Pour répondre à ces objectifs, des analyses quantitatives de la bibliographie (méta-analyse) ont été combinées à des approches expérimentales (figure 1). Des **méta-analyses** ont été conduites : 1) pour estimer les besoins énergétiques et protéiques d'entretien et de croissance des caprins, ovins et bovins ; ainsi que certaines lois de réponses à l'alimentation (méta-analyses 1 et 2); 2) pour valider ou invalider l'usage de différentes équations et coefficients

utilisés par le système d'unité d'alimentation INRA avec les fourrages des régions chaudes, (méta-analyse 3). Les méta-analyses 1 et 2 ont été valorisées dans la publication 1 consacrée à l'évaluation des besoins de caprins, ovins et bovins tropicaux, la publication 2 portant sur les lois de réponses de ces mêmes animaux à l'alimentation. Les méta-analyses 3 ont été valorisées dans le projet de publication 4.

L'objectif principal de l'étude expérimentale était de valider les estimations des besoins d'entretien et de production obtenus par méta-analyse. Le dispositif (figure 2) a été conçu pour étudier l'effet de gradients d'apport énergétique (4 niveaux) et protéique (3 niveaux) ainsi que leurs interactions sur certaines réponses zootechniques d'ovins Black-Belly et de caprins Créoles (ingestion, digestibilité, bilan azoté, croissance). Quarante-huit animaux (24 agneaux et 24 chevreaux) ont été répartis dans 12 lots de 4 animaux dont 2 agneaux et 2 chevreaux. Ce dispositif a été répété une fois.

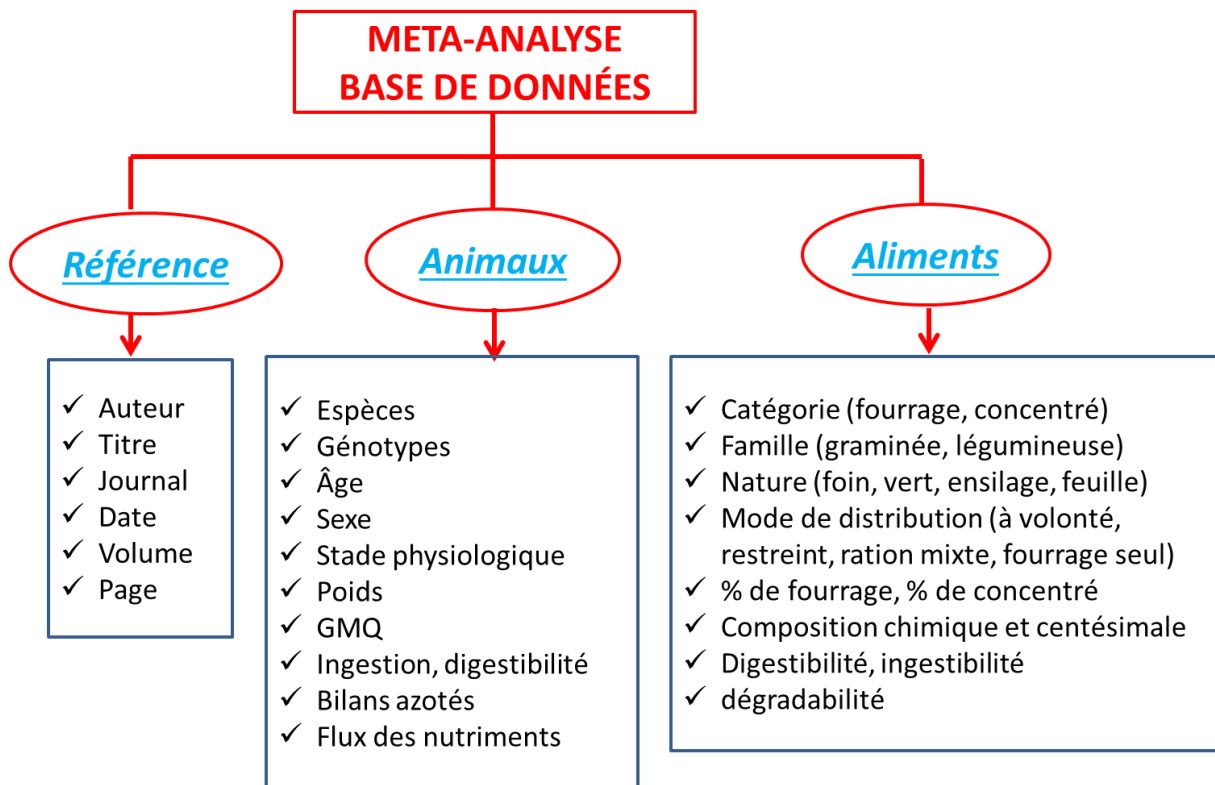


Figure 1: Structure générale et contenu des bases de données pour les méta-analyses.

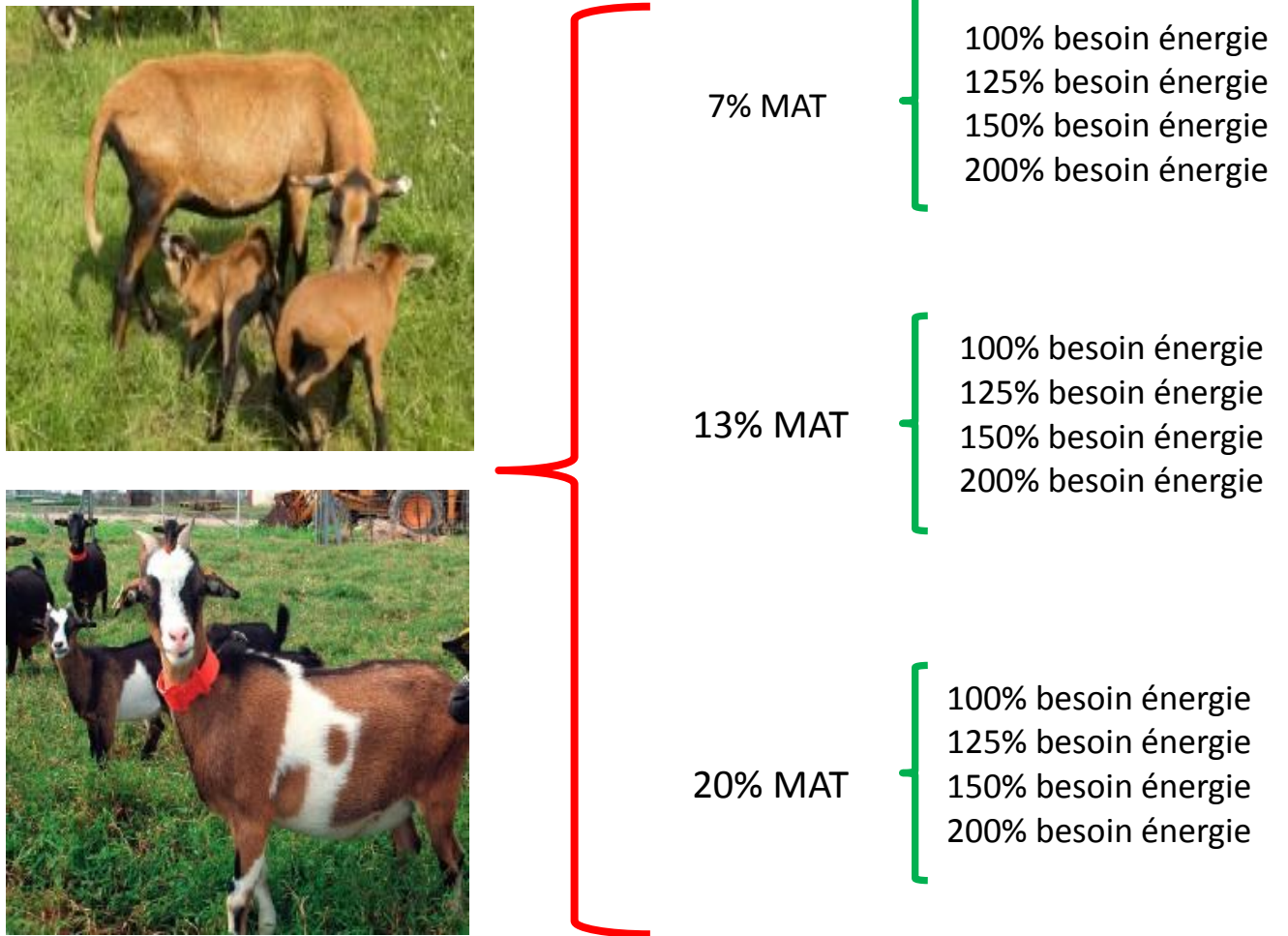


Figure 2 : Schémas du dispositif expérimental

CHAPITRE 2

RÉSULTATS

PUBLICATION 1

Publié dans le journal Animal

Besoins nutritionnels des ovins, caprins et bovins dans les climats chauds. Une méta-analyse

Les systèmes d'élevage mis en place dans les pays des régions chaudes sont généralement différents de ceux des pays tempérés, en raison de nombreux facteurs (Delgado et al., 1999). L'environnement climatique, caractérisé par une température élevée combinée ou non avec une humidité élevée est plus stressant pour les ressources végétales et animales. Les régimes alimentaires consommés par les animaux sont de moindre valeur nutritive, car d'une part, les fourrages sont plus riches en fibres et plus pauvres en protéines et d'autre part, le recours aux aliments concentrés est faible du fait de contraintes économiques. Les performances de production des animaux sélectionnés dans les régions tempérées sont meilleures que celles des animaux des régions chaudes, mais ces derniers sont généralement plus adaptés à leur environnement.

Malgré les différences mentionnées précédemment, les recommandations pour l'alimentation des animaux d'élevage dans les régions chaudes sont encore largement fondées sur des normes produites à partir des ressources biologiques des régions tempérées (INRA, 1988; ARC, 1984; NRC, 1985). Cependant la partition des nutriments entre la production et l'adaptation, la vitesse de croissance et la composition corporelle, influencent l'efficacité alimentaire (Berg et Butterfield, 1976). Par conséquent, les besoins nutritionnels des animaux d'élevage dans les régions chaudes et tropicales pourraient différer des normes d'alimentation des pays tempérés (INRA, 1988 ; ARC, 1984 ; NRC, 1985 ; CSIRO, 2007 ; NRC, 2007).

Bien que des études aient été menées sur des ovins tropicaux (Paul *et al.*, 2006), caprins tropicaux (Mandal et al., 2005) et bovins tropicaux (Paul *et al.*, 2004), il n'existe pas à notre connaissance de travaux d'intérêt plus large, basés sur de grandes bases de données ayant pour objectif de quantifier les besoins des ruminants dans les régions tropicales.

L'objectif de cette étude est de quantifier via une méta-analyse, les besoins énergétiques et protéiques pour l'entretien et la croissance de caprins, d'ovins et de bovins viande dans l'environnement d'élevage des régions chaudes.

Nutritional requirements of sheep, goats and cattle in warm climates. A meta-analysis

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Energy and protein nutrition of ruminants

The objective was to update energy and protein requirements of growing sheep, goats and cattle in warm areas through a meta-analysis study of 590 publications. Requirements were expressed on metabolic LW ($MLW=LW^{0.75}$) and LW^1 basis. The maintenance requirements for energy were 542.64 and 631.26 kJ ME/kg $LW^{0.75}$ for small ruminants and cattle, respectively, and the difference was significant ($P<0.01$). The corresponding requirements for 1 g gain were 24.3 kJ ME without any significant effect of species. Relative to $LW^{0.75}$, there was no difference among genotypes intra-species in terms of ME requirement for maintenance and gain. However, small ruminants of warm and tropical-climate appeared to have higher ME requirements for maintenance relative to LW than temperate-climate ones and cattle. Maintenance requirements for protein were estimated via two approaches. For these two methods, the data in which retained nitrogen (RN) was used cover the same range of variability of observations. The regression of digestible crude protein intake (DCPI, g/kg $LW^{0.75}$) against RN (g/kg $LW^{0.75}$) indicated that DCP requirements are significantly higher in sheep (3.36 g/kg $LW^{0.75}$) than in goats (2.38 g/kg $LW^{0.75}$), with cattle intermediate (2.81 g/kg $LW^{0.75}$), without any significant difference in the quantity of DCPI/g retained crude protein (40.43). Regressing metabolisable protein (MP) or minimal digestible protein in the intestine (PDI_{min}) against retained crude protein (RCP) showed that there was no difference between species and genotypes, neither for the intercept (maintenance = 3.51 g/kg $LW^{0.75}$ for sheep and goat vs 4.35 for cattle), nor for the slope (growth = 0.60 gMP/gRCP). The regression of DCP against ADG showed that DCP requirements did not differ among species or genotypes. These new feeding standards are derived from a wider range of nutritional conditions than existing feeding standards as they are based on a larger database. The standards seem to be more appropriate for ruminants in warm and tropical climates around the world.

Keywords: warm climates, ruminants, energy, protein, requirements

Implications

Despite a shortage of relevant studies, it appears that energy and protein requirements in tropical and warm regions are different from energy and protein requirements in temperate regions. In tropical areas, ME requirements of small ruminants for maintenance are higher, while production requirements are identical. Consequently, the total energy requirement for a similar level of production is also higher. With regard to protein, maintenance, production and consequently total requirement would be similar in both environments.

Introduction

Farming systems in southern countries are generally quite different from that in temperate countries (Delgado *et al.*, 1999) because of the following factors: (1) climatic environment, (2) diets with lower nutritional value; and (3) animal genotypes. However, the feeding recommendations for farm animals in tropical and warm regions are still largely based on standards established in temperate regions (ARC, 1984; INRA, 1989; NRC, 2007). The adaptation to diet and climatic condition affect nutrients partition, animal growth, body composition and, consequently, energy and protein requirements (Berg and Butterfield, 1976). The nutrient requirements of animals in tropical and warm regions could differ from those described in feeding standards for temperate countries. Studies on tropical livestock have focused on sheep (Paul *et al.*, 2006), goats (Mandal *et al.*, 2005) and cattle (Paul *et al.*, 2004) under the same condition with local breeds. However, to our knowledge, there is no recent work that has focused on the requirements of ruminants in tropical regions using a large database in order to take into account the maximum diversity of animal genotypes and dietary systems.

The objective of this study was to determine energy and protein requirements of growing ruminants in tropical and warm countries by running a meta-analysis on a large database built from independent studies.

Materials and methods

Data collection

A literature survey was conducted taking data from various international scientific reviews, easily-accessible regional reviews, reports and theses. Publications were selected to include several major criteria: 1) chemical composition of the diet; 2) data on animal performances; and (3) if possible, data on *in vivo* digestibility and nitrogen balance. In total, 589 publications representing 2225 different dietary treatments coming from feeding trials were used in the present study. In addition, another database containing published results on energy and protein requirements obtained via different methods (the calorimetric method, the slaughter method and Meta-analysis of feeding trials) has been analysed in order to compare the results in our study (see tables 1 and 2). The calorimetric method is conducted in respiration chambers to measure gas exchange, fasting heat production and energy lost via urine and methane with animals fed at maintenance level. The slaughter method is based on feeding trials with animals fed at two or more levels of intake (one of which approximates maintenance). The procedure measures both ME intake and retained energy (RE) as the change in body energy content of animals. The slope of the linear regression of RE on ME intake provides an estimate of efficiency of utilization of ME for RE and in growing animals equates to ME for growth. In the feeding trials method, the estimations of maintenance and growth requirements are made with potential growing animals fed continuous levels of energy to potentially cover less than one to several times the necessary requirements for a zero growth.

Table 1: ME requirement for maintenance ($\text{kJ/kg LW}^{0.75}$) and growth (KJ/g ADG) as derived from meta-analysis of results from the literature

Specie	Method	Genotype	Means		Min		Max		s.d	
			ME _m	ME _g	ME _m	ME _g	ME _m	ME _g	ME _m	ME _g
Sheep	Feeding	Tropical	423.7	17.6	339.8	14.7	546.8	19.7	71.2	2.7
		Temperate	361.2	16.4	329.7	10.9	434.7	20.6	50.0	5.0
	Slaughter	Tropical	460.0	32.7	364.6	23.9	525.8	42.0	47.9	12.7
		Temperate	453.6	16.4	382.2	16.4	495.6	16.4	49.6	
	Calorimetry	Tropical	407.0		360.4		465.8		53.5	
		Temperate	459.9		459.9		459.9			
Goats	Feeding	Tropical	451.9	27.7	375.9	21.4	555.7	42.4	57.4	6.4
		Temperate	443.1	25.6	415.0	17.6	472.9	31.5	19.2	6.4
	Slaughter	Tropical								
		Temperate	438.9		416.6		461.2		31.6	
	Calorimetry	Tropical	357.0		357.0		357.0			
		Temperate	424.6		331.0		523.7		72.0	
Cattle	Feeding	Tropical	556.5	23.9	411.6	21.4	630.0	26.0	72.3	1.7
		Temperate	518.3	17.2	420.0	12.2	638.4	31.5	64.3	7.0
	Slaughter	Tropical	492.2		419.2		600.6		59.6	
		Temperate	512.8		249.9		709.8		158.6	
	Calorimetry	Tropical	532.6		489.7		575.0		60.2	
		Temperate	519.5		415.8		615.7		74.5	

ME_m= metabolisable energy for maintenance; ME_g= metabolisable energy for gain; Min= minimum; Max= maximum; s.d= standard deviation

Table 2: Digestible crude protein requirement for maintenance (g/kg LW^{0.75}) and gain (g/g ADG) as derived from the meta-analysis of results from the literature

Specie	Method	Genotype	Means		Min		Max		s.d	
			DCPm	DCPg	DCPm	DCPg	DCPm	DCPg	DCPm	DCPg
Sheep	Feeding	Tropical	2.8	0.2	1.9	0.2	4.4	0.3	1.39	0.03
		Temperate	2.8	0.2	2.1	0.2	3.2	0.2	0.49	
Goats	Feeding	Tropical	2.9	0.2	2.1	0.1	3.9	0.3	0.56	0.08
		Temperate	2.7	0.2	2.1	0.2	3.1	0.2	0.44	
Cattle	Feeding	Tropical	3.2	0.3	2.9	0.1	3.4	0.4	0.25	0.12
		Temperate	2.8	0.3	2.2	0.2	3.5	0.5	0.38	0.14

DCPm= digestible crude protein for maintenance; DCPg= digestible crude protein for gain; Min= minimum; Max= maximum; s.d= standard deviation.

Animals and diets used in the feeding experiments

Overall, the data compiled covered more than 154 different breeds: 81 of sheep, 48 of goats and 25 of cattle. There were 10700 sheep, 3454 goats and 1855 cattle (including Zebu: 10%). For each species, three groups of genotypes were distinguished, genotypes from tropical and warm countries (75%), genotypes from temperate countries (16%) and crossbreeds (9%). This splitting was performed according to FAO classification; (<http://www.fao.org/docrep/004/X6532E/X6532E00.htm#TOC>, <http://eng.agraria.org/>, <http://www.ansi.okstate.edu/breeds/>). The regression of digestible crude protein intake (DCPI) and metabolisable energy intake (MEI) against average daily gain (ADG) to compare genotypes indicated that there was no significant difference (in slope or intercept) between tropical breeds and crossbreeds. Therefore, their data were pooled. Moreover, the regression of DCPI and MEI against ADG to compare sexes, potential for growth (high, medium and low) and different stages of age (from weaning to 8 months, from 8 to 12 months and over 12 months for small ruminants, and from weaning to 12 months, from 12 to 18 months and over 18 months for cattle) indicated that these three parameters have no significant effect on energy and protein requirements. Therefore, the data were pooled.

Diets were diverse, the majority being mixed diets (80%) and the rest being exclusively forage-based diets. Forages were also diverse: green or hay grass (54%), straw (30%), tree

foliage (7%) and hulls (4%). Concentrates were generally composed of conventional ingredients, though unconventional resources were also used.

Estimations, calculations and encoding

The most important parameters considered were growth, physiological stage, duration of observations, intake, digestibility and nitrogen balance. In addition, equations were applied to provide consistency and conventional expressions for certain variables. Thus, MEI per kg of live weight (MEI/LW, kcal/kgLW) was predicted from digestible organic matter intake per LW (DOMI/LW, g/kgLW) by the regression equation obtained on the “RUMENER” database containing only calorimetric measurements on sheep, goats and cattle (Sauvant *et al.*, 2011). The slope of 4.03 (MEI/DOMI) is similar to the value of 4.45 kcal ME/gTDN suggested by the NRC (2001).

$$\text{MEI/LW} = - 2.03 + 4.03 \text{ DOMI/LW} \quad (n=975, R^2 = 0.99, \text{RSD} = 11.3)$$

For the assessment of requirements in terms of metabolisable protein (MP), the French protein digestible in the intestine (PDI) system was applied using global and robust equations for prediction based on dietary CP and OMD taken from the INRA feed tables. The PDI content used for the calculation was the lower of the two estimates of calculated PDIN and PDIE supplied (INRA, 1978).

Publications were systematically coded to distinguish: 1) animal species; 2) genotypes within-species; 3) sexes; 4) potential for growth and (5) classes of age in order to compare their respective requirements. Two methods were used to estimate energy (ER) and protein requirements (PR). The first consisted of calculating ER and PR without taking into account the interaction between energy and protein. The second consisted of testing whether the interaction between protein and energy levels affects ER and PR. For this reason, we defined three classes of CP%DM based on CP requirement for maintenance and maximum growth and/or diet quality as follows: Low Protein (LP: 0 to 7%CP), Medium Protein (MP: 7 to 14%CP) and High Protein (HP: > 15%CP). Moreover, we defined four classes of energy based on energy requirement for maintenance (23 g DOM/kg LW^{0.75}) and maximum growth estimated from INRA table as follows: Very Low Energy (0 to 1 × maintenance), Low Energy (1 to 1.2×maintenance), Medium Energy (1.2 to 1.4×maintenance) and High Energy (>1.4×maintenance).

Statistical analyses

Inter-publication regressions of nutrient intake on ADG were calculated. Moreover, to test simultaneously the influences of species and genotypes on the intercept (maintenance requirements) and the slope (growth performance), analyses of variance and covariance were applied to the parameters. These meta-analyses were performed following the recommendations of Sauvant *et al.* (2008) using Minitab software (Minitab® 15.1.30.0., 2007). Outliers were removed when their normalised residues were > 3 .

Results

Description of dataset

Table 3 reports the statistical parameters of the major variables. As the level of intake and the requirements are generally expressed on various powers of the live weight, mainly 0.75 and 1, we performed a preliminary study to assess the best value to compare species. The inter-experiment relationship between the data on dry matter intake (DMI) and live weight (LW) after a log10 transformation indicated that intakes of sheep, goats and cattle are similar if they are expressed on the basis of $LW^{0.862}$ (Table 4, equation 1). Nevertheless, we have chosen to express the data on the basis of their $LW^{0.75}$ and LW^1 in order to compare our results with those given in the literature.

Table 3: Description of animal intake and average daily gain

Specie	Parameters	Unit	N	Means	Min	Max	s.d
Sheep	DOMI	g/kgLW/day	707	21.1	5.8	62.6	6.56
	DCPI	g/kgLW/day	619	3.2	-0.5	9.5	1.51
	ADG	g/kgLW/day	1217	4.8	-4.2	18.8	3.30
	forage	%	1085	50.4	0.0	100.0	27.07
Goats	DOMI	g/kgLW/day	312	21.9	3.3	60.1	9.02
	DCPI	g/kgLW/day	269	3.07	0.2	14.3	1.90
	ADG	g/kgLW/day	506	3.2	-7.7	22.4	2.60
	forage	%	457	56.0	0	100.0	25.07
Cattle	DOMI	g/kgLW/day	362	14.6	3.53	34.5	4.58
	DCPI	g/kgLW/day	354	2.0	0.1	5.2	0.83
	ADG	g/kgLW/day	372	2.6	-3.8	7.2	1.50
	forage	%	47	63.2	20.0	100.0	26.13

DMOI= digestible organic matter intake, DCPI= digestible crude protein intake, ADG= average daily gain, Min= minimum; Max= maximum; s.d= standard deviation.

Energy requirements for maintenance and growth

A first analysis showed that the difference between sheep and goats was not significant, and therefore their data were pooled. The results showed that the intercept for cattle was statistically different from the intercept of small ruminants, whereas the slopes were not different between the two groups. Ultimately, there was no influence of the genotype within species (Table 4, equation 2 and Figure 1). Moreover, the effect of protein level on energy requirement indicated that there was not a significant difference between the three classes of protein, neither for the intercept ($P>0.4$), nor for the slope ($P>0.22$), for the three animal species with significant difference between small ruminants and cattle only for the intercept (groups of equations (3) and (4), Table 4).

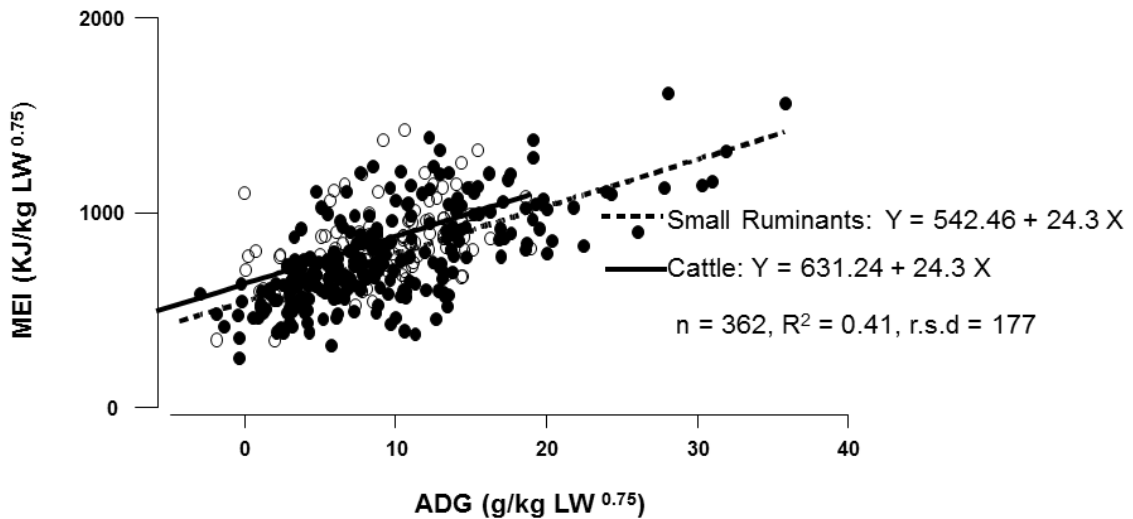


Figure 1: Relationship between MEI (kJ/kg LW^{0.75}/day) and ADG for small ruminants and cattle. The solid lines and closed circles are for small ruminants, and the dotted lines and open circles are for cattle.

The metabolisable energy concentration (MEC) of offered diets decreases with the measured ADG:

$$\text{MEC (Mcal/kgDM)} = 2.04 (\pm 0.03) + 0.027 (\pm 0.003) \text{ ADG/ LW}^{0.75} \quad (n=359, R^2=0.30, \text{RSD}=0.28)$$

$$\text{ADG g/kg LW}^{0.75} = - 6.91(\pm 1.82) + 7.01(\pm 0.8) \text{ MEC kcal/kg DM} \quad (n = 367, R^2 = 0.3, \text{RSD} = 5.35)$$

Logically, the NDF content of the diets is higher when ADG is lower:

$$\text{NDF (\%DM)} = 66.3 (\pm 0.84) - 1.44 (\pm 0.072) \text{ ADG/ LW}^{0.75} \quad (n=396, R^2=0.570, \text{RSD}=9.3)$$

Thus, it appears that diets were not iso-energetic according to the corresponding ADG, showing that ADG variations were essentially linked to the dietary energy concentration of diets offered *ad libitum*. Consistently, when animal diets have lower energy density and/or high fibre content, they are likely to produce more heat during digestion because of increased

chewing and physical gut work. Consequently, energy requirements should be better calculated in terms of net energy (NE) to be more independent of extra heat. Working from ME (kcal/kgDM), it is possible to calculate the metabolisability of the diets, $Q=ME/GE$, assuming a mean value of $GE=4.4$ Mcal/kgDM and NE for maintenance + fattening (NE_{mf}) as in the INRA systems (INRA, 1989). There was no influence of species when inputs are expressed in NE_{mf} as indicated in equation 5 (Table 4). Thus, we arrive at a common value for NE maintenance requirement of 297.8 ± 22.2 kJ $NE_{mf}/kg LW^{0.75}$ and a common value for growth requirement of 417.5 ± 1.13 kJ $NE_{mf}/gADG$.

To compare our results with similar proposals in the literature, we carried out analyses of variance on the data in Table 1 to assess the effects of species, genotypes and method (feeding trials, slaughter, calorimetry, reviews of meta-analyses obtained by feeding trials, published ME requirements tables). This produced 125 and 42 estimates of maintenance and gain requirements, respectively. For maintenance, there was a significant difference between cattle (529.2 ± 12.6 kJME/kg $LW^{0.75}$) and small ruminants (439.3 ± 10.08 kJME/kg $LW^{0.75}$) with no difference between sheep and goats and between genotypes. The comparison of our results [equation 2, Table 4] with data in Table 1 indicated that our maintenance requirement values were significantly higher for cattle (631.26 ± 17.5 vs 529.2 ± 12.6 kJME/kg $LW^{0.75}$) as for sheep and goat (542.64 ± 17.5 vs 439.3 ± 10.08 kJME/kg $LW^{0.75}$). Moreover, there was a trend ($p<0.09$) for an effect of method of requirements estimation (Table 1). Thus, for all species pooled, the lowest values were recorded for feed tables (432 ± 34 kJME/kg $LW^{0.75}$), while the highest values were recorded in the recent meta-analytic approaches (536 ± 21 kJME/kg $LW^{0.75}$). For requirement per unit ADG, there was no influence from any of the tested factors. Mean value was 23.1 ± 7.26 kJME/kgADG, which is close to our estimate of 24.3 ± 1.57 kJME/kgADG (equation 2). A similar study performed on the basis of LW^1 also found no difference between sheep and goats. The difference between cattle and small ruminants was significant, and the intra-species regression was given in equation 6 (Table 4). Thus, on a LW^1 basis, maintenance requirements for energy appeared higher for tropical small ruminants ($n=201$) than temperate small ruminants ($n=51$) and for small ruminants than for cattle ($P<0.01$). For cattle, there was no difference between genotypes ($n=106$). According to the power of the LW, ME requirement/kg ADG is slightly different (non-significant): 24.3 ± 1.57 expressed on a $LW^{0.75}$ basis and 22.66 ± 1.93 on a LW^1 basis. Based on NE intake, there was still a difference between small and large ruminants (Table 4, equation 7).

Table 4: Equations for prediction of energy requirements (MJ/kg LW^{0.75})

N°Equation	Equation	n	R ²	s.d
1	$\log_{10}DMI = -1.27 (\pm 0.02) + 0.862 (\pm 0.01) \log_{10}LW$	549	0.91	0.11
2	Global: $MEI/LW^{0.75} = Ei(\pm 17.5) + 24.3(\pm 1.57) ADG/LW^{0.75}$ (Ei = 542.64 for small ruminants and 631.26 for cattle)	362	0.41	177
3	LPSR: $MEI/LW^{0.75} = 494.5(\pm 18.9) + 18.03(\pm 3.32) ADG/LW^{0.75}$ MPSR: $MEI/LW^{0.75} = 538.5(\pm 18.9) + 18.03(\pm 3.32) ADG/LW^{0.75}$ HPSR: $MEI/LW^{0.75} = 544.8(\pm 18.9) + 18.03(\pm 6.32) ADG/LW^{0.75}$	333	0.39	186
4	LPC: $MEI/LW^{0.75} = 662.6(\pm 33.5) + 18.03(\pm 3.6) ADG/LW^{0.75}$ MPC: $MEI/LW^{0.75} = 683.5 (\pm 33.5) + 18.03(\pm 3.6) ADG/LW^{0.75}$ HPC: $MEI/LW^{0.75} = 637.8 (\pm 33.5) + 18.03(\pm 3.6) ADG/LW^{0.75}$	120	0.22	150
5	$NEI/LW^{0.75} = 297.8 (\pm 22.2) + 17.05 (\pm 1.13) ADG/LW^{0.75}$	360	0.39	121
6	$MEI/kgLW = Ei (\pm 8.13) + 22.66 (\pm 1.93) ADG/LW$ (Ei = 259.06 for tropical small ruminants. 243.4 for temperate small ruminants and 174.75 for cattle)	358	0.52	67.4
7	$NEI/LW = Ei (\pm 4.2) + 15.33 ADG/LW$ (Ei = 139.2 for small ruminants and 92.4 for cattle)	360	0.39	46.2

LPSR, LPC: Low protein for small ruminants and cattle, respectively.

MPSR, HPC: Medium protein for small ruminants and cattle, respectively.

HPSR, HPC: High protein for small ruminants and cattle, respectively.

MEI and NEI are expressed in MJ/ kg LW^{0.75}/day or MJ/kg LW/day.

Protein requirements for maintenance and growth

Requirements based on N retention

In the regression between DCPI (g/kg LW^{0.75}) and RN, there was an effect of species as indicated in equation 4 (Table 5) with a high value for sheep (3.36 ± 0.27), followed by cattle (2.81 ± 0.27) and goats (2.38 ± 0.27). Moreover, there was no influence of species on the slope of this equation, which represents growth requirements equal to 40.43 g DCPI/g fixed crude protein (Figure 2). Pooling estimations of DCP requirements published in the literature (n=32 publications, Table 2), reveals, as for energy, large differences across studies and no influence of species on the intercept (2.93 ± 0.57 gDCP/kg LW^{0.75}). Overall, the method had

no influence, but when results from meta-analysis were integrated (n= 4), values became significantly higher (3.59 ± 0.10 vs 2.81 ± 0.28 for small ruminants and cattle, respectively).

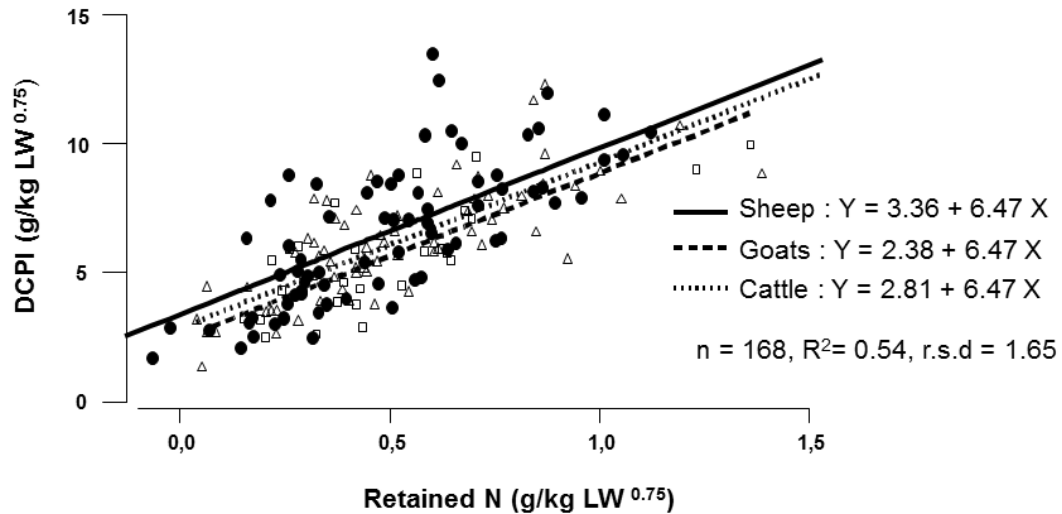


Figure 2: Relationship between DCPI (g/kg LW^{0.75}/day) and RN . Solid black lines and closed circles are for sheep. Squares and dashed lines are for goats. Triangles and dotted lines are for cattle.

The corresponding regression when the French digestible protein system (PDI) was used and when RN was expressed as RCP, the corresponding regression is given in equation 5 (Table 5) and the maintenance requirement in PDI (g/kg LW^{0.75}) equalled to 3.51 ± 0.16 for both sheep and goats and 4.35 ± 0.16 for cattle. Moreover, statistical analysis using the effect of energy level on DCP requirements indicated that there was no significant difference between energy level defined previously, neither on the intercept ($P > 0.2$), nor on the slope ($P > 0.4$), for the three animal species (equations 1, 2 and 3, Table 5).

Requirements based on ADG

There was no difference between species and genotypes for DCP requirement for maintenance (DCPm) (3.53 ± 0.32 gDCPI/kgLW^{0.75}). As the regression was not linear, the marginal DCP requirement/kg ADG (DCPg) decreases from 0.446 gDCP/kg ADG when ADG was close to 0.0 to 0.326 gDCP/kg ADG when ADG was 10 g/kg LW^{0.75} and to 0.206 gDCP/kg ADG when ADG was 20 g/kg LW^{0.75} (Table 5, equation 6). Considering the published growth requirement values, the 15 data in Table 2 do not yield significant differences between species, genotypes and methods, and the common value is an intermediate 0.30 ± 0.10 gDCPI/kg ADG. In addition, there was not a significant difference between energy level on DCPm and DCPg, neither for the intercept (P=0.2), nor for the slope (P=0.23), for the three animal species (equation 7, Table 5).

To explain certain differences between the two approaches, we studied the regression of RN on ADG. There was an influence of species on the constant of the relationship given in equation 8 (Table 5, Figure 3). Thus, at maintenance (ADG=0) a positive RN was obtained for the three animal species with a high value for cattle, goats and sheep. The value of the slope suggests that there was a gain of 17.5 g CP/100g of gain.

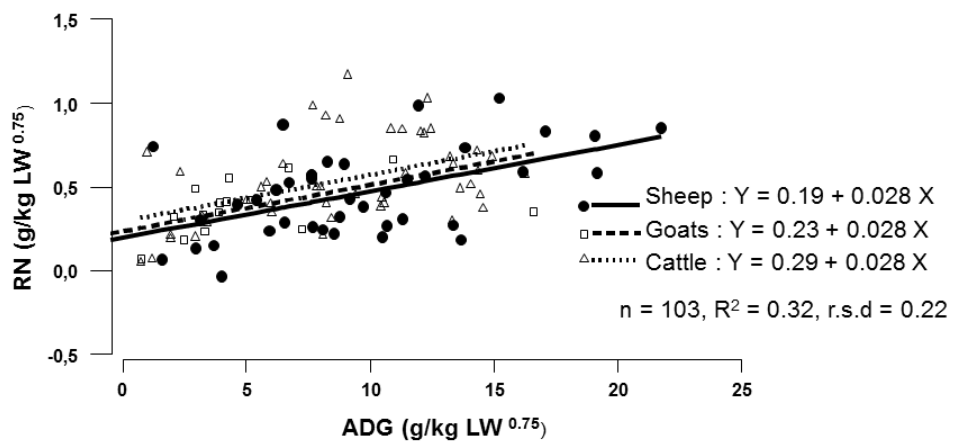


Figure 3: Relationship between RN and ADG (g/kg LW^{0.75}/day) . Solid black lines and closed circles are for sheep. Squares and dashed lines are for goats. Triangles and dotted lines are for cattle.

Table 5: Equations for prediction of protein requirements (g/kg LW^{0.75})

N°Equation	Equation	n	R ²	s.d
1	Sheep: DCPI/LW ^{0.75} /day= Ei(±0.4) + 5.55(± 0.89) RN (Ei= 2.51, 4.19,3.37 and 3.93g for very low, low, medium and high energy, respectively)	104	0.63	1.52
2	Goat: DCPI/LW ^{0.75} /day= Ei (±0.75) + 6.08(± 1.76) RN (Ei= 1.71, 2.54, 4.32 and 3.67 g for very low, low, medium and high energy, respectively)	39	0.59	1.51
3	Cattle: DCPI/LW ^{0.75} /day= Ei(±0.31) + 5.83(± 0.64) RN (Ei= 2.47, 3.11, 3.94 and 3.52g for very low, low, medium and high energy, respectively)	119	0.60	1.41
4	Global equation: DCPI/LW ^{0.75} /day = Ei (± 0.27)+ 6.47 (± 0.46) RN/ LW ^{0.75} (Ei = 3.36 for sheep. 2.38 for goats and 2.81 for cattle)	168	0.54	1.66
5	PDI/LW ^{0.75} /day = Ei(± 0.16) + 0.60 (± 0.044) RCP/ LW ^{0.75} (Ei = 3.51 for small ruminants and 4.35 for cattle)	164	0.59	0.98
6	DCPI/LW ^{0.75} /day= Ei(± 0.29) + 0.40(± 0.062) ADG – 0.005(± 0.0035) ADG ² (Ei= 2.79. 3.26. 3.8 and 4.27 g/kgLW ^{0.75} for very low, low, medium and high energy, respectively)	474	0.59	1.68
7	Global equation: DCPI/ kgLW ^{0.75} /day = 3.53(± 0.32) + 0.446(± 0.054) ADG - 0.0058 (± 0.002) ADG ²	331	0.41	2.1
8	RN g/kgLW ^{0.75} /day= Ei(± 0.043) + 0.028(± 0.0047) ADG (Ei = 0.19. 0.23 and 0.29 g for sheep. goats and cattle)	103	0.32	0.22

Relationship between energy and protein requirement

As illustrated in Figure 4, there was a fairly high positive correlation between CP levels and ME supplied. This correlation, which is the outcome of the calculations of all the diets that were made to cover a given level of requirements in each publication, shows that a meta-design does not separate energy and protein aspects, knowing that ADG and NR were more correlated with energy than with protein supplies. Therefore, energy appears globally more limiting than protein.

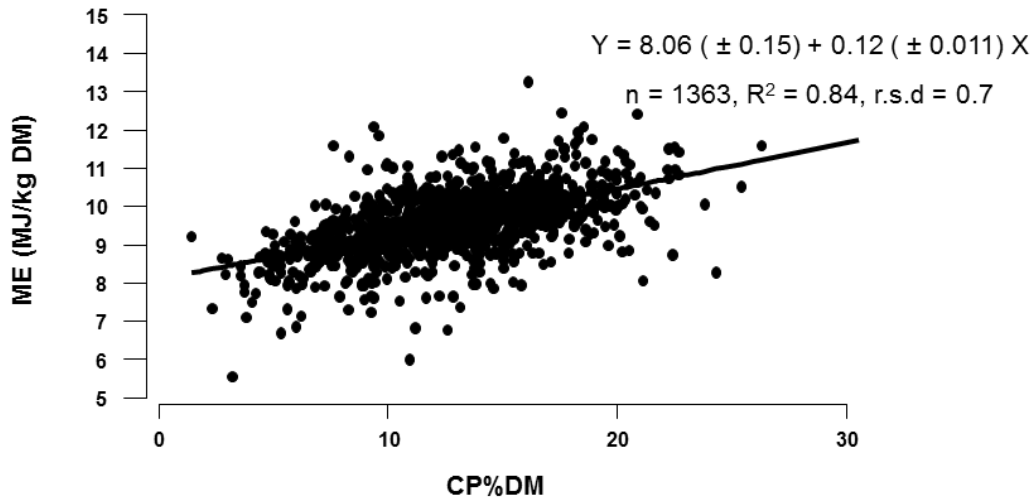


Figure 4: Relationship between ME and CP content of the rations.

Discussion

Our work does carry some limitations due to the data available. Thus, as no publications have compared temperate and warm genotypes together, the genotype comparison had to be studied across publications, which is not a very effective procedure. Moreover, the number of data with body composition was too low to take this aspect into consideration precisely. Indeed, it is known that for the same gain, protein and energy cost may be different depending on the body composition (Galvani *et al.*, 2008). We tried to take into account this aspect indirectly by comparing animal sexes, growth potential and ages without any effect on requirements for the three animal species. However, some previous study such as NRC (2000) and Luo *et al.* (2004b) suggested greater requirements for intact males compared with females and male castrates. Moreover, the effect of age is not well studied, but some findings with ruminants indicated decreasing requirements with age (Luo *et al.*, 2004b).

Energy requirement for maintenance and growth

A limit of this work is that ME, in all probability, is not the energy type best suited to assessing the actual energy value of feeds and fibre-rich diets. Most European energy systems are effectively built on the proposals of Van Es (1972) showing that the efficiency of conversion (k) of ME to NE was closely and positively linked to the ratio $Q=ME/GE$, or dietary ME/kgDM, which is closely linked to OMD. Consequently, for cell wall-rich low-ME/kgDM diets, which are more frequent when observations are closer to low performance levels in our database, the difference between ME and NE is more important. Consequently, higher losses of energy as extra heat can be expected when diets are given to low-performing animals. This effect was confirmed by equations linking ADG to ME/DM or NDF%DM. However, net energy systems, which *a priori* would appear better suited, are far from standardised worldwide and are often based on equations with unknown accuracy. Nevertheless, we ran calculations on NE combining maintenance and growth, in line with French practice, and the species differences disappeared on the $LW^{0.75}$ basis.

Influence of measurement method

In general, maintenance requirements depend on production type such as lactating or dry female, and requirements estimated from productive animals during feeding trials are higher than those recorded for animals fed at or below maintenance as in the calorimetric method (Paul *et al.*, 2004). During feeding trials, the animal passes through several physiological stages, each of which consumes more or less dry matter and energy, thus affecting the maintenance needs (Mandal *et al.*, 2005). Our analysis of published data (Table 1) to compare method confirms these tendencies. As a general rule, low energy supplies were more frequently obtained by experimentally limiting supply than by giving cell wall-rich feed. This difference can partly explain the fairly high values obtained here, although we believe our approach provides maintenance requirement values that are more relevant to operational practice for ruminants receiving poor diets.

Influence of species and intra-species genotypes

The ranking between cattle and small ruminants is directly linked to the value of the power of LW. When ME was expressed on a $LW^{0.75}$ basis, cattle had significantly higher MEM compared with small ruminants. In contrast, when ME was expressed on a LW^1 basis, small ruminants had higher MEM than did cattle. The choice of exponent 0.75 and 1 is relevant to compare species. Otherwise, on using 0.86 as exponent, the difference between species disappears.

Our estimates of the ME requirements of tropical ruminant livestock are higher than published values for either tropical or temperate genotypes. Hence, Paul *et al.* (2003) estimated ME requirement for Indian sheep and cattle at 533 and 596 kJ/kg $LW^{0.75}$, respectively. However, Mandal *et al.* (2005) and Luo *et al.* (2004b) estimated the ME requirement for goats at 453 and 487 kJ/kg $LW^{0.75}$, respectively. When ME was expressed on a LW^1 basis, tropical small ruminant genotypes had higher ME than temperate small ruminant genotypes. The NRC (2007) indicated that there was no general comparison available for small ruminants between intensive-farmed genotypes and genotypes in developing countries. More precisely, for goats, Luo *et al.* (2004b) were unable to detect genotype (indigenous mature and dairy goats) influence on MEM. For cattle, the lack of significant difference in MEM and MEg between genotypes may be due to the small number of data on temperate genotypes used in this dataset. Tropical genotypes, which are not generally selected for muscle deposition, tend to be fatter than temperate genotypes, and consequently the energy cost of LW gain (MEg) is higher (Early *et al.*, 2001).

Influence of environmental conditions and feeding levels

Under high temperature conditions, the energy required to dissipate body heat increases, which can raise the energy requirement of the animal (CSIRO, 2007). Fibrous diets generally increased heat production, visceral energy consumption, energy costs of intake and chewing, energy expenditure and consequently ME requirements (Goetsh *et al.*, 1997). The high values of energy requirements obtained can be attributed to the high rates of metabolism in visceral organs and tissues during growth which increases their maintenance costs compared with full-grown animals (CSIRO, 1990).

Live weight gain requirements

The energy requirement for 1 g ADG was estimated to be 24.3 kJ ME (Table 4). This estimate is inside the range of values published in the literature (13.73 to 27.9) for Indian sheep, goat and cattle (Paul *et al.*, 2003 and 2004; Mandal *et al.*, 2005). It is also inside of the range of published values attributed to temperate animals. The NRC (1989), NRC (1981, 2001) and INRA (1989) have published values of 20.62, 30.28 and 31.5 for sheep, goat and cattle, respectively. Methods used, livestock genotypes, animal age and consequently body composition could explain these variations (Rohr and Daenicke, 1984).

Protein requirements for maintenance and growth

Two approaches were applied to estimate protein requirements. The method that emerged here as most accurate is based on N retention data. Unfortunately, the number of data obtained with this method is fairly limited compared with growth-based predictions. Moreover, N balance studies can also lead to biases of overestimation of N retention (Spanghero and Kowalski, 1997).

Protein requirements based on N retention

DCP requirement estimates for maintenance are 3.36, 2.38 and 2.81 g/kg LW^{0.75} for sheep, goat and cattle, respectively. These values fall within the range of published values (1.96 to 4.43 g/kg LW^{0.75}) on tropical-genotype livestock under warm climates, but are higher than those published on temperate-genotype livestock under temperate climates. In fact, the range of variation of published data for tropical goats is 0.74 to 3.83 gDCP/kg LW^{0.75} (Sengar, 1980; Akinsoyinu, 1985). For temperate goat genotypes, DCP maintenance requirements have been

estimated at 2.82 g and 2.13 g/kg LW^{0.75} by the NRC (1981) and the INRA (1989), respectively. However, the estimated value for cattle (2.81 g/kg LW^{0.75}) is 12% less than the INRA value of 3 g/kg LW^{0.75} for large and dairy cattle and the CSA (1975) value of 3.2 g/kg LW^{0.75}, but is closest to the 2.84 g/kg LW^{0.75} proposed by Van Es (1972). Differences between temperate and tropical genotypes can be attributed to the lower growth potential of tropical genotypes. Gihad (1976) obtained a value of 1.95 g/kg LW^{0.75} for tropical sheep. The differences can be attributed to the different body composition between adult and growing animals.

Protein requirements were also expressed according to the MP system (INRA, 1978; NRC, 1981) using equation 5. The regression of MP to RN resulted in values of 3.51 for small ruminants and 4.35 for cattle. The MP requirements for small ruminants (2.65 and 2.2 g/kg LW^{0.75} for both sheep and goats) proposed by the INRA (1980), and the value of 2.19 given by AFRC (1998) for goats are much lower than our estimate. Medeiros (2001) and Ferreira (2003) reported lower values for Saanen kids (1.31 and 2.16 g/kg^{0.75} BW, respectively), whereas Luo *et al.* (2004c) reported higher values for Angora (3.35 g/kg LW^{0.75}), meat, dairy and indigenous (3.07 g/kg LW^{0.75}) goats. The recommendations of 2.87 and 2.39 gMP/kg LW^{0.75} attributed, respectively by AFRC (1993) and CSIRO (1990), are lower than our estimates for sheep. The value obtained for cattle (4.35 g MP/kg LW^{0.75}) is higher than some previous results. Veras *et al.* (2008) obtained a value of 4.03 g/kg LW^{0.75} for MPm. Our result was higher than the value of 3.8 and 3.25 g/kg LW^{0.75} adopted by NRC (2000) and INRA (1980), respectively. The high values for MP requirements found here are likely the outcome of two factors. The first factor is that we opted for PDIE feed values (assuming energy is limiting in the rumen), which are higher than PDIN values (assuming protein is limiting in the rumen) and thus assumes that N recycling is sufficient to entirely restore N deficit. The second factor was the simultaneous effects of energy levels and protein levels and the fact that energy appeared more limiting as it better explains variations in ADG or RN.

The high protein requirement for maintenance obtained can be attributed to the high rates of metabolism in visceral organs and tissues during growth, which increases their maintenance costs compared with fully-grown animals (CSIRO, 1990). It is known that there is a direct relationship between rate of protein synthesis and metabolic rate of animals of different species (Waterlow, 1968), and that rates of protein synthesis are higher in young growing animals than in adults (Connors *et al.*, 2008). Many estimates of MP requirements for gain have been derived by separate prediction of protein concentration in body weight gain,

resulting in a wide range of MP requirements for gain. Differences in MP requirements are effectively attributable to diet quality. Animals given diets composed of poor-quality roughage are likely to have low N retention and high protein requirement.

Requirement based on ADG

The estimated DCP maintenance requirement of 3.53 g/kg LW^{0.75} is inside the range of values (1.96 to 4.43 for sheep; 2.12 to 3.90 for goat; 2.73 to 3.51 for cattle) for tropical breeds. Published values for temperate livestock range from 2.16 to 3.2 for sheep, from 2.13 to 3.19 for goat and from 2.78 to 3.00 for cattle (Table 2).

The slightly higher published estimates for tropical vs temperate animals could be partly explained by environmental factors (temperature, diets). Fibre content, positively correlated to protein requirement for maintenance and protein requirement, is also reported to increase with increasing ratio of roughage to concentrate (Goetsh *et al.*, 1997). High temperature has been associated with increased requirement of absorbed amino acids for growth in ruminants (Bunting *et al.*, 1992). Comparing the two approaches (N retention vs ADG), we hypothesise that the higher requirements reported for the ADG method can be explained by the fact that positive nitrogen retention can be observed at ADG=0, which may be due to the recycling of nitrogen necessary for tissue regeneration. The protein requirement for gain is estimated at 0.30 g DCP/g gain, but is curvilinear depending on animal growth (at 0.44 for ADG at close 0 to 0.206 when ADG is 20 g/kg LW^{0.75}). The curvilinear response of protein requirements with ADG probably reflects biological phenomena tied to the body composition of growing animals (water, fat, etc.). Overall, protein requirements decrease to an average growth level of approximately 20 g/kg LW^{0.75}, which corresponds to the peak growth potential recorded with tropical ruminant livestock. Beyond this potential, growth is enriched with lipids, which decreases protein retention per unit of growth (Byers, 1982).

Globally, our estimates tend to be slightly higher than previous published estimates for temperate ruminants. These results could be explained by leaner body growth in temperate genotypes. Our estimates fall within the published range for tropical ruminant livestock - that is, 0.26 to 0.31, 0.17 to 0.34 and 0.19 to 0.45 for sheep, goat and cattle, respectively.

Animals reared under normal experimental conditions in a feeding trial that coincides more with real feeding practices (animals in batches, feed distributed *ad libitum* or restricted) show more intensive or less metabolism and protein turnover due to animal activity (McDonald *et*

al., 1995). Hence, estimates of energy and protein requirements reported from analysis of intake versus growth performance are likely to be slightly higher than the values reported for balance trials and respiration calorimetry used in other international systems for feeding standards.

Conclusion

This study based on feeding and digestive trials including a large diversity of diets and animal genotypes representative of tropical and warm areas provides updated values for maintenance and growth requirements. Species ranking is dependent on the power coefficient of LW. The main conclusion of this study is the higher energy and protein requirements of tropical and warm-area ruminants compared with those proposed in the international feed system standards such as NRC, ARC, INRA and AFRC tables. Moreover, we found little or no differences between species.

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PUBLICATION 2

Publié dans le journal Animal

Réponses des ruminants en croissance à l'alimentation dans des conditions chaudes.

Une méta-analyse

Les pratiques classiques d'alimentation des animaux d'élevage sont basées sur l'évaluation des besoins en nutriments. Les recommandations alimentaires doivent permettre aux animaux de maximiser leur potentiel de production. Cette approche cohérente avec l'intensification de l'élevage ne prend pas suffisamment en compte les réponses de l'animal à la variation de régime alimentaire en termes d'efficacité de l'alimentation raisonnée à l'échelle du système d'élevage et du territoire, ainsi que l'impact sur la composition des produits animaux, les émissions (azote, méthane) et sur la santé et le bien-être des animaux.

Certains auteurs dont Sauvant (1992), ont suggéré d'enrichir la pratique classique d'alimentation avec le concept de réponses multiples des animaux aux régimes alimentaires. Ce concept pourrait être particulièrement intéressant dans les régions chaudes où la stratégie est souvent de valoriser par les animaux, les biomasses végétales disponibles. Les animaux sont rarement nourris pour exprimer leur potentiel, pour des raisons économiques et de disponibilité d'aliments concentrés.

Comparativement aux régions tempérées, les ruminants dans les régions chaudes valorisent souvent des aliments pauvres et ou déséquilibrés (Wilson et Minson, 1980). A notre connaissance, il n'y a pas de synthèse de données relatives aux réponses animales à ce type de régime. Dans le chapitre précédent, les besoins en énergie et en protéines ont été revus et mis à jour par une méta-analyse d'une grande base de données. Cette base de données contenait une grande diversité de types de régimes alimentaires et d'animaux. Dans ce chapitre, nous étudions (intra essai) les réponses des animaux à l'alimentation.

Response of growing ruminants to diet in warm climates: a meta-analysis

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Nutrition and performance of ruminants

The aim of this work was to establish the response of growing sheep, goats, and cattle to different nutritional environments. Data from 590 publications representing 2225 treatments were analysed. The results showed that each 10% increase in NDF was accompanied by 0.11 g/kg Live weight (LW) and 0.32 g/kg metabolic live weight ($LW^{0.75}$) decreases in DMI. Otherwise, the response of DMI to crude protein (CP%DM) content was curvilinear ($P<0.01$), without any significant difference in the slope between species. The percentage of concentrate (%CC) affected DMI curvilinearly, without any significant difference between species. This meta-analysis demonstrated the negative linear effect of NDF and quadratic effect of CP concentration on organic matter digestibility (OMd). For growth performance, the three species responded curvilinearly to variations in metabolisable energy intake (MEI MJ/kg $LW^{0.75}$) and digestible crude protein (DCPI g/kg $LW^{0.75}$) intake ($P<0.01$). At the same level of MEI, average daily gain (ADG) varied with CP content of the diet and only the intercept differences were significant between the three levels ($P=0.07$). At the same level of DCPI, ADG varied with energy level (below maintenance [LE--], 1 to 1.2× maintenance [LE-], 1.2 to 1.4× maintenance [ME+-], and >1.4, corresponding to maximum growth [HE+]). No significant difference was observed between LE-- and LE- and no significant difference was observed between ME+- and HE+. For nitrogen balance, no difference was observed between species for a given level of nitrogen intake (NI).

Keywords: warm climates, meta-analysis, growth, intake, digestibility

Implications

Currently, the challenges of animal nutrition are diverse. They include not only performances, but also efficiency and environment. The concept of multicriteria animal responses to diet constitute a good way for the farmers and advisers to manipulate the itineraries of production in order to obtain a production system that is both productive and respectful. The current study gives new information on animal responses under warm conditions, with comparison of different animal species and genotypes. Some equations could be used in software decision support for predicting multiple responses of farmed ruminants.

Introduction

Classical feeding livestock practices are based on the assessment of requirements and feeding recommendations that allow animals to express their potential for production. All the feed unit systems are built on this principle (Agabriel *et al.*, 2007). This approach, which is strictly based on potential for performance, does not take into account sufficiently the animal's responses to diet variation in terms of feed efficiency and also the impact of diet on product composition, waste, and on animal health and welfare. Some authors (Sauvant, 1992) have suggested enriching the classical feeding concept of satisfying the requirements with the concept of multicriteria responses of animals to diets. This concept could be particularly interesting in tropical and warm countries where the major strategy is to valorise biomass through animals that are not always fed at the level of the requirements.

Compared to temperate regions, ruminants in tropical and warm regions generally subsist under poor nutritional conditions (Wilson and Minson, 1980). Practically, animals' responses to this type of diet have almost never been synthesised in the literature. In a previous paper (Salah *et al.*, 2014), energy and protein requirements were revisited and updated by a meta-analysis of a large database. As this database contains a large diversity of types of diets and animals, it was decided to explore intra-experiment variations of the data to build empirical models of animal responses across a wide diversity of animals and nutritional practices mainly in tropical and warm conditions.

Materials and methods

Data collection

A careful literature survey was conducted to extract data from various international scientific reviews, easily accessible regional reviews, reports, and theses. Publications were selected if simultaneously they contained at least the following data: the co-occurrence data on: 1) chemical composition of the diet (especially OM, CP and NDF); 2) intake and total tract digestion of diets (especially DM or OM, CP); growth; 3) animal growth. In some publications these last information were completed with nitrogen balance (urine, faeces). In total, 589 publications representing 2225 different dietary treatments were pooled to be used in the present study: 325 publications on sheep (n=1287 treatments); 145 on goats (n=544 treatments); and 119 publications on cattle (n=394 treatments).

Animals and diets used in the feeding experiments

For each species, three groups of genotypes were distinguished (genotypes from tropical and warm countries, genotypes from temperate countries, and crossbreds of the two). This splitting was performed according to FAO classification [<http://www.fao.org/docrep/t1300t/t1300t00.htm#Contents>; <http://www.fao.org/docrep/004/X6532E/X6532E00.htm#TOC>, <http://eng.agraria.org/>, <http://www.ansi.okstate.edu/breeds/>]. The classification of areas into tropical and warm and temperate countries was performed according to following classification (<http://aragonbilingue.educa.aragon.es/frances/wp-content/uploads/2010/01/climatsterre.pdf>). Warm climate is composed of equatorial climate (Amazonia, some African regions), tropical humid (some African regions, West Indies, some South American regions), desert climate (some African regions, Asia, Arabia) and monsoon climate (Southeast Asia, India...).

Diets were diverse. The majority were mixed diets (80%); the rest were exclusively forage-based diets. Forages were also diverse: green or hay grass (54%); straw (30%); tree foliage (7%); and hulls (4%). More than 80 plant species were used as feed. Concentrates were generally composed of conventional ingredients such as barley, corn, wheat bran, rice bran, proteaginous seeds and oilseeds (soya, groundnut, peas, sunflower...). Unconventional resources (carob pulp, chicken litter, cassava chips, etc.) were also used as complements.

Estimations, calculations, and encoding

Some estimates were applied when data were lacking in the publications and when good predictors were available. Thus, when the OM content and OMD were lacking, while DM digestibility was measured, they were estimated from measured DM multiplied by 0.9 and 1.05, respectively. These last two values are derived from analyzes of databases feeding trials conducted with temperate and tropical feed. Otherwise, the MEI was predicted from digestible organic matter intake (DOMI) by the regression equation obtained on a large dataset extracted from the database RUMENER, which pooled calorimetric measurements for sheep, goat, and cattle (Sauvant and Giger-Reverdin, unp.).

MEI = -2.03 + 4.03 DOMI (n=975, R²=0.99, RSD=11.30); RSD is the residual standard deviation

Publications were systematically coded to distinguish animal species and the corresponding genotypes. Beyond this *a priori* encoding, *a posteriori* encodings based on statistical analyses were performed to identify the experiments that having a large intra-experiment variation of dietary energy (over 5 points of variation in OMD), protein levels (over 3%), NDF level (over 5%), and percentage of concentrate (over 20%). This approach was complemented by a statistical method based on the study of the residues coming from an analysis of variance of the quantitative factor (OMD, CP levels, NDF levels) including the effect publication as the explanatory factor. These standardized residuals were submitted again to a second ANOVA including the publication effect. The experiments that have a value greater than the standard error of the model residue were then selected. A coding has been performed to identify publications for which data varied on the following criteria: CP content, NDF, organic matter digestibility, percentage of concentrate. These codes allow the identification of several sub-data bases used depending on the objective as stated by Sauvant et al 2008. Such an approach of intra-publications analysis of animal response has already been used by Loncke *et al.* (2009) and Nozière *et al.* (2011).

Statistical analyses

Animal responses were calculated through intra-publication regressions using variance-covariance analysis. In a first step, statistical analysis was performed independently for each animal species to test the difference between genotypes, sexes, potential for growth and age. In particular, General Linear Model analyses were conducted to study the response of ADG or

nitrogen excretion to MEI ($\text{MJ/kg LW}^{0.75}$), DCP ($\text{g/kg LW}^{0.75}$) and NI ($\text{g/kg LW}^{0.75}$). The effects mentioned above were not significant and accordingly they were not considered in the following steps of the meta-analysis. The data base of sheep goats and cattle have been pooled into a single meta-data base.

These meta-analyses were performed following scrupulously the recommendations of Sauvart *et al.* (2008) using Minitab software (Minitab® 15.1.30.0., 2007). The statistical model used to fit the data was:

$$Y_{ij} = B_0 + \text{EXPi} + B_1 X_{ij} + B_i X_{ij} + B_2 X_{ij}^2 + e_{ij}$$

where Y_{ij} is the explained variable, B_0 the intercept, EXPi the qualitative effect of experiments, species on the intercept, B_1 the coefficient of linear regression of the covariable, B_i the effect of species on the slope of the regression (interaction covariable \times species), B_2 the coefficient of quadratic effect of the covariable, and e_{ij} the random residuals. When alone the experiment effect was treated as a fixed one, knowing that it can include influences of factors.

Results

Description of dataset

The main statistics of the variables of the database are presented in Tables 1 and 2. Whatever the animal species, large variations of dietary NDF and CP which constitute limiting factors under tropical and warm conditions were observed among treatments. For all animal responses, there was no significant difference between genotypes. A classical negative correlation was observed between CP (%DM) and NDF (%DM).

$\text{CP (\%DM)} = 20.29 (\pm 0.51) - 0.14 (\pm 0.01) \text{NDF (\%DM)}$ ($n = 1616$, $n_{\text{exp}} = 240$, $R^2 = 0.83$, $\text{RSD} = 1.85$, n_{exp} = number of experiments).

Table 1: Statistical description of the dietary variables (% of DM) and percentage of concentrate in the ration in the database for ruminants in tropical and warm climates.

Parameters	Species	Unit	n	Mean	Minimum	Maximum	s.d.
NDF	Sheep	% DM	905	48.20	10.52	88.72	15.66
	Goat	% DM	445	50.96	16.17	92.20	13.23
	Cattle	% DM	278	56.62	13.27	87.89	12.75
CP	Sheep	% DM	1193	13.40	1.40	27.60	3.87
	Goat	% DM	520	13.41	1.75	35.43	4.39
	Cattle	% DM	394	11.81	3.00	19.67	3.02
CC	Sheep	% DM	1053	47.78	0.00	98.32	25.90
	Goat	% DM	444	42.32	0.00	92.11	23.50
	Cattle	% DM	224	34.23	0.00	80.00	17.61

NDF= neutral detergent fibre, CP= crude protein, CC= concentrate, n= number of treatments; s.d.= standard deviation.

Table 2: Statistical description of animal performance in the database

Parameters	Species	Unit	n	Mean	Minimum	Maximum	s.d.
DMI	Sheep	kg/d	1223	0.96	0.22	2.56	0.38
	Goats	kg/d	512	0.62	0.10	2.77	0.31
	Cattle	kg/d	394	4.53	1.52	14.04	1.85
FN	Sheep	g/d	328	6.08	0.83	33.13	3.12
	Goats	g/d	123	4.27	0.20	19.94	2.86
	Cattle	g/d	202	31.06	7.16	64.40	11.45
UN	Sheep	g/d	323	5.66	0.33	22.40	4.66
	Goats	g/d	123	3.35	0.18	14.10	3.02
	Cattle	g/d	199	24.47	2.30	93.80	13.51
RN	Sheep	g/d	349	4.95	-8.70	31.20	4.73
	Goats	g/d	133	3.96	-5.43	18.03	3.36
	Cattle	g/d	240	25.70	-8.79	88.96	16.70
ADG	Sheep	g/d	1217	130.31	-94.00	388.00	94.17
	Goats	g/d	522	57.36	-193.00	326.00	51.24
	Cattle	g/d	383	392.20	-582.50	1210.00	215.60
OMD	Sheep	%	733	64.84	31.78	91.15	10.22
	Goats	%	335	67.21	35.40	93.15	10.73
	Cattle	%	374	61.14	28.63	89.90	7.13

DMI= dry matter intake, FN= faecal nitrogen, UN= urinary nitrogen, RN= retained nitrogen, ADG= average daily gain, OMD= organic matter digestibility, n= number of treatments; s.d= standard deviation.

Dry matter intake (DMI)

Effect of NDF content on DMI

Only the publications for which NDF content between treatments varied beyond the value of 5% DM were used. The intra-experiment relationships between dietary NDF and DMI are negative and presented in equations 1 and 1b (Table 3). A significant difference between small ruminants (sheep + goats) and cattle was observed in the intercept ($P < 0.01$). The ranking of the species was inversed according to the power of LW. In contrast, for each equation, no significant difference was observed in the slope, showing parallel responses for the three animal species.

Effect of CP content on DMI

Only the publications for which CP content between treatments varied over 3% DM were used. Dietary CP had a significant and quadratic effect ($P < 0.01$) on DMI. Whatever the power unit of the LW, no significant difference was observed between sheep and goats. Therefore, their data were pooled. Moreover, there was no significant interaction between species and the linear component of CP. The ranking of the small ruminants and cattle was reversed according to the power of LW used, with a significant difference between the small ruminants and cattle in the intercept (equations 2 and 2b: Table 3). The use of CP%DM and NDF%DM in the same model can ameliorate the precision of the model. For these analyses we used the publications for which CP and NDF content between treatments varied simultaneously over 3% DM and 5% DM for CP and NDF respectively. The RSD were lower when CP and NDF were combined.

Table 3: Influence of CP (%DM) and NDF (%DM) on intake of sheep, goats and cattle fed with mixed diets in warm areas

Equation number	Equations	n	nexp	R ²	s.d.
1	DMI (g/kg LW)=Ei (±0.86) – 0.11 (±0.02) NDF% (Ei=39.17 ±0.51 for SR and 29.65 ±0.51 for cattle)	870	223	0.82	2.75
1b	DMI (g/kg MLW)=Ei (±2.08) – 0.32 (±0.04) NDF% (Ei=91.33 ±2.08 for SR and 106.75 ±2.08 for cattle)	863	223	0.92	6.52
2	DMI (g/kg LW)=Ei (±0.96) + 1.34 (±0.14) CP% – 0.04 (±0.05) CP% ² (Ei=24.55 ±0.96 for SR and 15.77 ±0.96 for cattle)	1035	266	0.92	2.79
2b	DMI (g/kg MLW)=Ei (±2.36) + 3.45 (±0.34) CP% – 0.100 (±0.012) CP% ² (Ei=48.01 ±2.36 for SR and 65.65 ±2.36 for cattle)	1034	266	0.92	6.77
3	DMI (g/kg LW)=Ei (±2.18) – 0.074 (±0.020) NDF% + 1.07 (±0.18) CP% – 0.031 (±0.007) CP% ² (Ei=30.25 ±2.18 for SR and 21.73 ±2.18 for cattle)	596	148	0.93	2.65
3b	DMI (g/kg MLW)=Ei (±5.16) – 0.23(±0.05) NDF% + 2.58 (±0.43) CP% – 0.08 (±0.02) CP% ² (Ei =66.15 ±5.16 for SR and 85.29 ±5.16 for cattle)	594	148	0.92	6.26

n= number of treatments; nexp= number of experiments; s.d= standard deviation; SR= small ruminants, DMI= dry matter intake; CP= crude protein content; NDF= neutral detergent fiber content; Ei= coefficient of the intercept; LW= live weight; MLW= metabolic live weight = LW^{0.75}.

Effect of percentage of concentrate on DMI

Only the experiments where forage was distributed *ad libitum* and where the proportion of concentrate varied (>20% between treatments) were used for this analysis. The percentage of concentrate had a quadratic and significant ($P < 0.01$) effect on total DMI (TDMI) and forage DMI (FDMI), with a similar response between species (equations 1, 1b, 2, and 2b: Table 4). The maximum value of DMI was obtained with 60% of concentrate (Figures 1, 2).

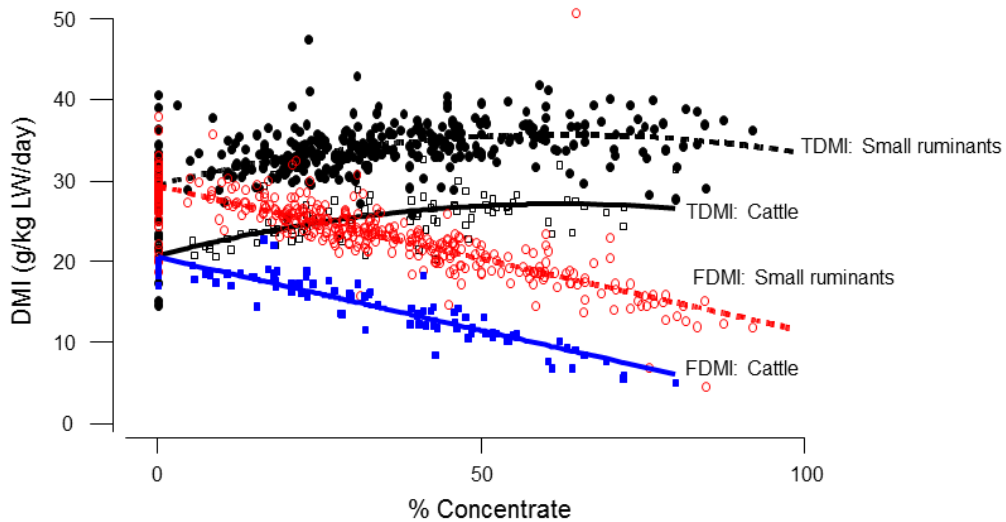


Figure 1: Influence of percentage of concentrate in the ration on DMI (g/kg LW^1). Closed circles and dotted lines indicate TDMI of small ruminants; open squares and solid black lines indicate TDMI of cattle; dotted red lines and open circles indicate FDMI of small ruminants; solid blue lines and squares indicate FDMI of cattle. (TDMI and FDMI are total and forage dry matter intakes). Y values are corrected for the experiment effect.

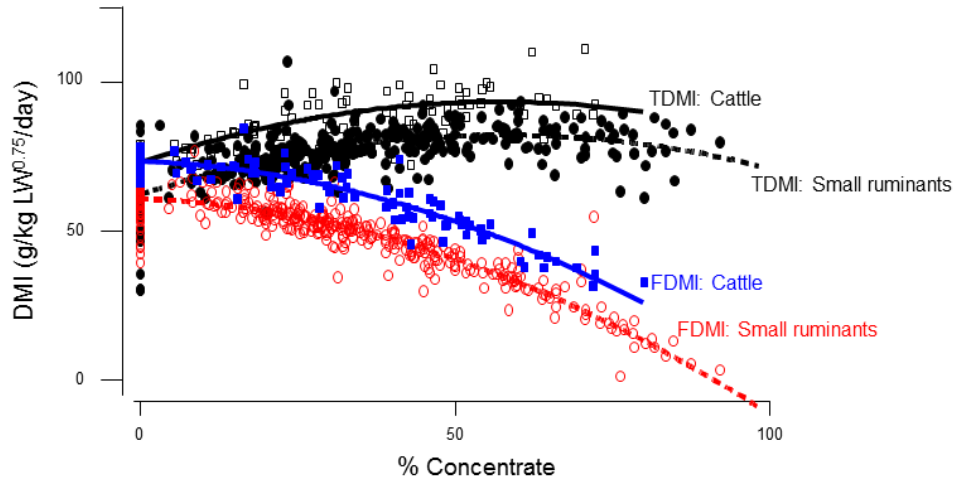


Figure 2: Effect of percentage of concentrate in the ration on DMI ($\text{g/kg MLW} = \text{LW}^{0.75}$). Closed circles and dotted lines indicate TDMI of small ruminants; open squares and solid black lines indicate TDMI of cattle; dotted red lines and open circles indicate FDMI of small ruminants; solid blue lines and squares indicate FDMI of cattle. (TDMI and FDMI are total and forage dry matter intakes). Y values are corrected for the experiment effect.

Organic matter digestibility (OMd)

Effect of NDF and CP on OMd

A linear negative effect of NDF and a positive quadratic effect of CP were observed on OMd without any difference between species (equations 3 and 4, Table 4). According to this equation, the theoretical maximum OMd was achieved at the level of 24% CP. The marginal response of OMd declined linearly in function of CP, thus, it was more marked for low CP content, for instance, when CP=5% DM, $d\text{OMd}/d\text{CP}=1.53$, while when CP=20% DM, $d\text{OMd}/d\text{CP}=0.33$. To go further in the interpretation and integration of data, all the data were pooled and treated with the three above-mentioned covariables: NDF%; CP%; and CP^2 . The intra-experiment generic regression is given in equation 5 (Table 4). The relationship between chemical composition and DMI indicated that the equation between OMd and chemical composition includes a confounding effect of both chemical composition and intake level.

Table 4: Influence of percentage of concentrate (%CC), CP (%DM) and NDF (%DM) on intake, total tract digestibility and nitrogen balance for sheep, goats and cattle fed with mixed diets in warm areas

Equation number	Equations	n	nexp	R ²	s.d.
1	TDMI (g/kg LW)=Ei (±0.65) + 0.20(±0.04) %CC – 0.0016 (±0.0005) %CC ² (Ei=29.39 ±0.65 for SR and 20.75 ±0.65 for cattle)	492	118	0.92	3.28
1b	TDMI (g/kg MLW)=Ei (±0.45) + 0.70(±0.09) %CC – 0.0061 (±0.0013) %CC ² (Ei=61.80 ±0.45 for SR and 72.80 ±0.45 for cattle)	498	118	0.92	7.29
2	FDMI (g/kg LW)=Ei (±0.49) – 0.07(±0.03) %CC – 0.0018 (±0.0004) %CC ² (Ei=28.70 ±0.49 for SR and 20.56 ±0.49 for cattle)	476	112	0.96	2.46
2b	FDMI (g/kg MLW)=Ei (±1.06) – 0.08 (±0.06) %CC – 0.0064 (±0.0009) %CC ² (Ei=60.50 ±1.06 for SR and 73.30 ±1.06 for cattle)	472	112	0.95	5.32
3	OMd%=86.4 (±1.33) – 0.37 (±0.02) NDF%	537	135	0.90	3.39
4	OMd%=46.45 (±1.90) + 1.93 (±0.29) CP% – 0.04 (±0.01) CP% ²	687	174	0.86	4.27
5	OMd%=73.15 (±2.50) – 0.32 (±0.03) % NDF% + 1.12 (±0.20) CP% – 0.035 (±0.007) CP% ²	1083	294	0.89	3.86
6	RN g/kg MLW= - 0.21 (±0.04) + 0.14 (±0.01) DCPI – 0.0032 (±0.0010) DCPI ²	287	77	0.93	0.10

n= number of treatments; nexp= number of experiments; s.d= standard deviation; SR= small ruminants, DMI= dry matter intake; CP= crude protein content; NDF= neutral detergent fiber content; FDMI= forage dry matter intake; TDMI= total dry matter intake; CC%= percentage of concentrate in the ration; OMD= organic matter digestibility; DCPI= digestible crude protein intake; RN: retained nitrogen; Ei= coefficient of the intercept; LW= live weight; MLW= metabolic live weight = LW^{0.75}.

Growth performance

Effect of MEI on growth performance

The effect of MEI on ADG has been tested using only publications for which Organic matter digestibility varied largely (> 5% between treatments). There is a relationship between the digestibility of organic matter and energy intake for diets eaten ad libitum. To take into a consideration the effect of MEI independently of protein and to check for any interaction between energy and protein, the data were split according to three levels of CP (% DM) based on the CP requirement for maintenance and whole growth and diet quality. The three classes of % CP were low (0 to 6.99%: LCP), medium (7 to 14.99%: MCP), and high (>15%: HCP). For the three classes, the ADG increased linearly with increasing MEI, without any difference between species (Figure 3). There was a tendency toward a significant difference between the three classes in the intercept (P=0.02), but not in the slope (P=0.7). At the level of 0.0243 MJ, mean of the value of ME requirement of cattle and small ruminants (Salah *et al.*, 2014), the ADG were of 2.35, 0.18 and -4.39 g for HCP, MCP and LCP, respectively.

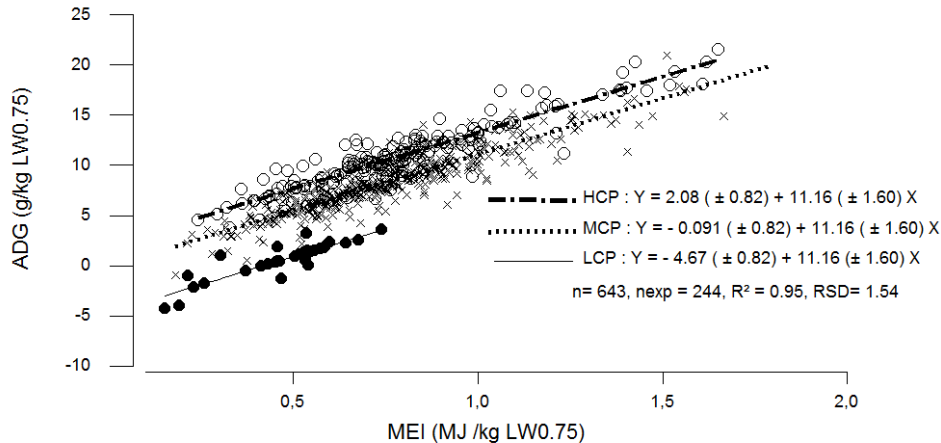


Figure 3: Effect of ME intake (MJ/kg LW^{0.75}/day) on average weight gain (g/kg LW^{0.75}/day). Dotted lines and open squares indicate high CP (HCP); solid lines and crosses indicate medium CP (MCP); dotted lines and closed circles indicate low CP (LCP). Y values are corrected for the experiment effect.

Effect of DCPI on growth performance

To take into a consideration the effect of DCPI independently of energy and to check again any effect of energy x protein interaction on ADG, we chose four levels of energy by dividing DOMI by $23 \text{ g/kg LW}^{0.75}$, which approximately corresponded to the maintenance requirements (INRA, 1989). The four levels of energy were very low energy (LE--: less than $0.99 \times \text{maintenance}$), low energy (LE-: from 1 to $1.2 \times \text{maintenance}$), medium energy (ME+ -: 1.2 to $1.4 \times \text{maintenance}$), and high energy (HE+ > $1.4 \times \text{maintenance}$). The value 1.4 corresponded to the maximum growth estimated by INRA tables. For the four classes, ADG increased quadratically with increasing DCPI, without any difference between species (Figure 4). Statistical analysis indicated that there was no significant difference neither for the intercept ($P > 0.05$), nor for the slope ($P > 0.05$) between very low energy group and low energy group. So the data were pooled together in the same group (LE). Moreover, there was no significant difference neither for the intercept ($P > 0.05$), nor for the slope ($P > 0.05$) between medium energy and high energy group. So their data were pooled in the same group (HE). At DCPI=0, a negative ADG ($-0.59 \text{ g/kg LW}^{0.75}$) was observed with LE, while the HE class had a small positive ADG ($2.29 \text{ g/kg LW}^{0.75}$). When the supply is covering the maintenance requirements considered as equal to $2.85 \text{ g/kg LW}^{0.75}$ (mean value of the three species according to Salah el al, 2014), the ADG was positive and equal to 6.47 and 3.56g for HE and LE group, respectively. Otherwise, the marginal animal responses to increased DCPI were not significantly different between LE and HE; thus, the two responses were similar, suggesting that there was no energy x protein interaction ($P = 0.54$).

The marginal ADG response was 1.21 g/g DCPI when DCPI was low ($1.0 \text{ g/kg LW}^{0.75}$). It decreased to 0.59 and 0 g/g DCPI when DCPI was increased to $7.0 \text{ g/kg LW}^{0.75}$ and $12.7 \text{ g/kg LW}^{0.75}$, respectively. In contrast to energy, the maximum ADG was within the range of the observed data of DCPI (for group HE). The range of DCPI was much smaller for the LE group than for the HE group, showing that there was no experiment exploring high DCPI combined with low energy.

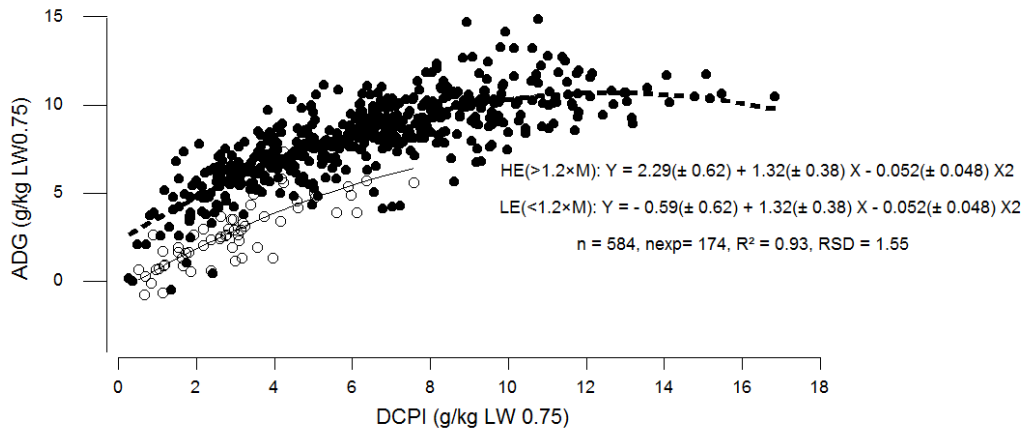


Figure 4: Effect of DCPI (g/kg LW^{0.75}/day) on body weight gain (g/kg LW^{0.75}/day). Dotted lines and closed circles indicate a level of energy that is above the medium to high (AME-H); solid black lines and open circles indicate a level of energy that is low to below the medium (L-BME). Y values are corrected for the experiment effect.

Nitrogen utilisation

Effect of NI on FN, UN, and RN

For this part, only studies dealing with variations of nitrogen content (>3% CP between treatments) were considered. The statistical analysis indicated that FN and UN increased linearly with increasing NI, without any difference between species (Figure 5). The slope was higher for UN than FN and the value of the intercepts was not significantly different from zero for FN and equal to 0 for UN. RN increased quadratically with increasing NI. Therefore, when NI=0, the marginal response of dRN/dNI was high (0.63 g/g, in Figure 6) and when NI increased, dRN/dNI decreased (for instance, 0.37 g/g when NI=3.0 g/kg LW^{0.75}). The large range of dietary N content of the dataset allowed to explore the value of the minimum excretion of UN which could be retained to assess the metabolic losses of N in urine which could be compatible with life. The intra-experiment equation between UN (g/kg LW) and digestible N intake (DNI, g/kgLW) was indicated in equation 7, Table 4. When DNI = 0, which correspond to a minimum level of supply to stay alive, the excretion of UN is of 0.063±0.008 g/kgLW.

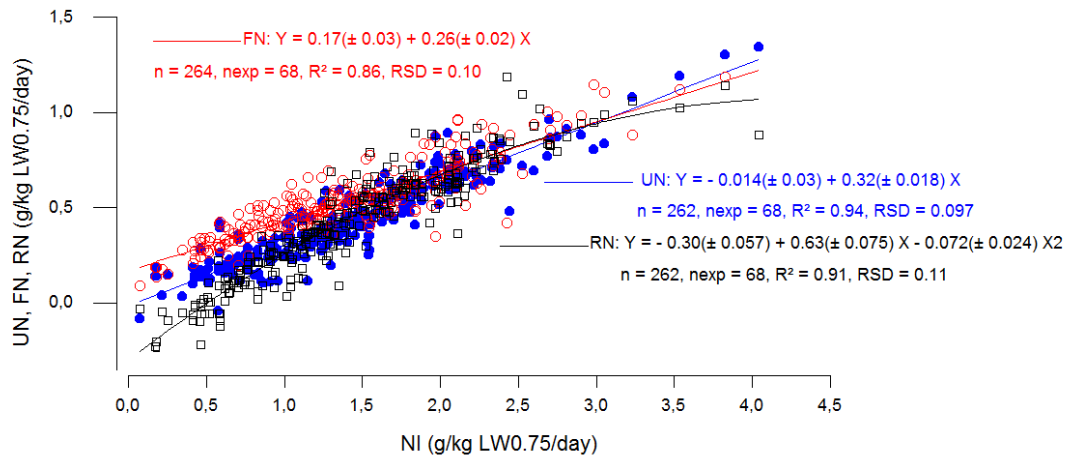


Figure 5: Intra-experiment influence of NI on UN, FN, and RN. Y values are corrected for the experiment effect.

Discussion

This paper presents an approach complementary to that of the companion paper on requirements calculated using the same database (Salah *et al.*, 2014). With these two papers, we chose to use two different approaches (inter-publication analysis for nutrient requirements and intra-publication analysis for animal responses). In the present paper, the statistical treatment of the variations within experiments, pooled in groups having similar targets, allowed us to calculate responses of animals to the corresponding feeding practices. As far as we are aware, such a combined approach has never been systematically performed through meta-analyses. In the companion paper (Salah *et al.*, 2014), the within-study variations were ignored and only the variations across publications were considered and treated, assuming that they were mainly caused by experimental contexts, particularly animal attributes corresponding to various levels of nutritional requirements (LW, potential for growth, physiological stage of growth, etc.).

Dry matter intake***Effect of NDF content on DMI***

The negative effect of NDF on DMI is classically explained by fill value of fibre, which is linked to either the limitation of chewing time, to a maximum of approximately 900–1000 min/d, or to its negative effect on passage rate (Assoumaya *et al.*, 2007). Recently, Meyer *et al.* (2010) indicated that at the level of 50% NDF, DMI (g/kg LW^{0.75}) was 74.8 and 91.4 for small ruminants and cattle, respectively. Presently, the respective values were 75.3 and 90.7 g/kg LW^{0.75}. Arelovich *et al.* (2008) indicated a decrease of 0.21 g DMI/kg LW^{0.75} per unit of NDF. The value was 0.32±0.040 g DMI/kg LW^{0.75} per unit of NDF in this study. Compared to all cited studies, the present work took into account much more data and provides more reliable values.

Effect of dietary CP content on DMI

The effect of CP content on DMI has been studied before (Fenderson and Bergen, 1976). The effect of CP is not linear and DMI reaches a plateau when CP exceeds a threshold of approximately 15% of DM with a maximum of intake obtained at the level of 17% CP, with parallel responses for sheep, goats, and cattle. These results are consistent with several authors such as Roffler *et al.* (1986) who found that the marginal increase in DMI equated to nearly 900 g at 12% CP and that the increase in DMI was only 40 g/d with CP of around 18%. The increase in DMI until the level of 15–17% CP can be explained by an increased rate of digestion of OM in the rumen (Assoumaya *et al.*, 2007) and by the better nitrogen status of the animals and the microbes in this range of CP content.

The plateauing in DMI when the CP content exceeded 17% was likely because the potential for growth was reached. Furthermore, the fact that the intra-publication statistical analysis indicated a negative relationship between CP and NDF contributed indirectly to the influence of CP on DMI. However, the association of NDF and CP in the same prediction equation allowed us to achieve a slightly better precision than with either CP or NDF alone, as already suggested by Demarquilly and Andrieu (1992) and Assoumaya *et al.* (2007). May be, the careful calculation of rumen undegradable (RUP) and degradable (RDP) proteins could allow to go further in the explanation of the DMI response to increase of CP simultaneously to a decrease in NDF. This global approach would have an advantage compared to the classical

traditional method of fill unit mainly formatted for roughages. The fill value of concentrate is inferred from the fact of the existence of digestive interactions in mixed diets.

Effect of percentage of concentrate on DMI

Total DMI increased with percentage of concentrate, but the marginal response tended to diminish until a level of concentrate of approximately 60%. The same type of results has been currently reported (INRA, 1989; Nousiainen *et al.*, 2008), who observed in dairy cow a quadratic effect of concentrate level on DMI. A first possible explanation of the decrease in DMI at very high levels of concentrate is the fact that the potential for growth was reached and, consequently, the regulation of DMI became more and more metabolic. Beyond this aspect, with high levels of concentrate, there is classically a radical alteration in the profile of the microbial fermentation in the rumen, with an increase of glucogenic precursors such as propionate and sometimes lactate (Allen, 2000).

Organic matter digestibility

The present meta-analysis demonstrated a quadratic effect of CP concentration on OMD and corroborated results of previous studies. Nousiainen *et al.* (2008) indicated that OMD marginal response decreased from 0.41 to 0.21 g/kg when dietary CP concentration increased from 130 to 180 g/kg of DM in dairy cows. In the present study, on all types of ruminants the corresponding values were 0.89 and 0.49 g/kg of DM, respectively. Furthermore, in the Bovidig database on cattle used to calculate the new INRA feed unit for ruminants (Sauvant and Nozière, 2013), the intra-experiment relationship between OMD and CP was very close to the present one and slightly more precise ($OMd = 50.7 + 1.88 CP - 0.045 CP^2$, $n=209$, number of experiment=80, $RSD=2.30$). The positive effect of CP on OMD, despite an increase in DMI as seen before, was likely the outcome of an increase in the activity of rumen microorganisms allowed by a greater N availability (Agle *et al.*, 2010). The cumulated influences of dietary CP on DMI and OMD result in a large increase in digestible organic matter intake (DOMI) and therefore in ME intake as a response to dietary CP which was also partly the outcome of the simultaneous increase of NDF as CP decreased.

Effectively, as frequently observed, there was a negative linear relationship between NDF content and OMD as indicated by Assoumaya *et al.* (2007) who studied only ration based on forage or containing less than 20% of concentrate. It appeared that OMD of sheep, goat, and

cattle responded similarly to increased NDF content. In contrast, it has been observed previously that goats and cattle were likely less sensitive than sheep receiving poor quality food (Dulphy *et al.*, 1994).

Growth performance

Effect of MEI on growth performance

The present meta-analysis demonstrated a linear effect of MEI on ADG ($P < 0.10$), with parallel responses for the three animal species which is an original result. The mean response of ADG was 42.3 g/ Mcal ME or 10.1g/MJ ME. Mean ADG response values of 63.2 and 67.8 for growing lambs, 41.5 for goats and 65.5 g ADG/Mcal MEI for cattle, respectively have been previously established on less data by Mahgoub *et al.* (2000), Lu and Potchoiba (1990), and Medina *et al.* (2010).

It has been possible to split the data into three groups according to the level of dietary CP. There was no interaction between energy and protein on animal growth. Such as additivity between energy and protein for growth on a large number of data is original. At the same level of MEI, a higher ADG was observed with HCP level, followed by MCP and LCP levels. Lammers and Heinrich (2000) fed heifers ration with LP, MP, and HP and reported that ADG was improved by 9% in heifers fed a diet containing HP to ME ratio. The same results were observed in sheep and goats (Sultan *et al.*, 2010; Hwangbo *et al.*, 2009). Increasing dietary CP levels causes a change in the process of intake and digestion in the rumen and also improves absorption of by pass protein that contribute to metabolisable protein available for growth (Nolan and Leng, 1983). These changes improve the energy balance, allowing more nitrogen to be accreted and increasing ADG (Kioumarsis *et al.*, 2008).

Effect of DCPI on growth performance

Our results indicated the existence of a quadratic and positive effect of DCPI on ADG, which was confirmed by the quadratic effect of DCPI on RN. The maximum response of ADG was obtained at approximately 150g/kg DM of CP. Our results were globally in agreement with other works (Titi *et al.*, 2000). On much fewer treatments, Haddad *et al.* (2001) observed in growing lambs that 16% CP was the optimum level to promote growth.

The increase in protein intake was accompanied by an increase in the proportion of protein that escaped ruminal fermentation, resulting in an increased amount of protein reaching the abomasum and small intestine to be absorbed as amino acids, which subsequently improved animal growth (Shahzad *et al.*, 2011). As for MEI supply, there was no interaction between the DCPI and MEI, confirming the additivity between the two supplies for growth. At the same level of DCPI, a higher ADG would have been observed with a high level of energy. The increase of DCPI caused the same ADG responses in HE and LE groups. A high ADG was observed for HE level compared to LE level at the same level of DCPI.

Nitrogen utilisation

Numerous researchers have reported that increasing NI is accompanied by an increase in FN and UN (Yan *et al.*, 2006; Moore *et al.*, 2004). Previous results obtained by the analysis of a dataset from 25 studies indicated that the slope of the linear relationship between NI and FN or UN varied from 0.20 to 0.39 and 0.38 to 0.68, respectively (Castillo *et al.*, 2000; Huhtanen *et al.*, 2008; Kebreab *et al.*, 2010; Weiss *et al.*, 2009). The corresponding values obtained in our studies were 0.26 for FN and 0.32 for UN. This difference can be attributed to age of animals. Our results were obtained in growing ruminants, whereas previous authors worked with adult animals (dairy cows).

The new French unit system has proposed to quantify this loss by calculating the rumen protein balance (RPB) in diet formulation (Sauvant and Nozière, 2013). This RPB is the major criteria to predict UN excretion. The increase of UN with increased NI can be attributed to the high blood and plasma urea nitrogen, which cause high nitrogen clearance rates of the kidney and increase urea excretion via urine (Khon *et al.*, 2005). A debate is remaining about the minimum loss of N in urine which can be adopted as endogenous loss in protein unit system. Our debate allowed to predict the UN which correspond with digestible nitrogen intake (DNI) = 0, situation which, contarily with NI=0, allowed survival. For this reason, the proposed value of 0.063 g/kg LW UN loss has been proposed recently for the new protein unit system in France (Sauvant *et al.*, 2014). Some authors noted a linear relationship between NI and RN (Archibeque *et al.*, 2007) and others noted a quadratic relationship with a decreasing marginal effect (Zanton and Heinrichs, 2008). This suggests that the intake was in excess of the animals' capacity to utilise nitrogen efficiently.

Nitrogen balance can vary with the method used for collecting and preserving urine and faeces (Isaksson and Sjogren, 1967). Nitrogen retention can differ between slaughter method and feeding. Rattray and Joyle (1970) indicated that balance method appeared to overestimate N retention compared to slaughter method. The data introduced in our analysis was based only on feeding and balance technique.

Conclusions

This meta-analysis yielded new information on multi-criteria responses of growing ruminants reared under warm conditions and their comparison with those reared under temperate conditions using the same database. This approach is original in the context of the development of agro-ecology in livestock research to optimize various functions both productive and non-productive. This approach is also original on a nutritional point of view because it is complementary with the conventional approach based on estimation of requirements. This last one has limitations in the context of tropical areas where the objective is often to valorise available biomass rather than balancing diets. This analysis also shows the limitations of conventional experiments often built to analyse one factor, one function, rather than analysing multiple responses of the animal. This last point is a challenge for the future. This study, comparing animal species, also questions the relevance of basis of expression of input and requirements (live weight *versus* metabolic weight).

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PUBLICATION 3

Soumis pour publication dans le journal *Animal Physiology and Animal Nutrition*

Effet du niveau énergétique et protéique et leurs interactions sur les bilans azotés et les performances de croissances des ovins Black Belly et des caprins Créole.

Comme indiqué dans les chapitres précédents, les recommandations d'alimentation sous les tropiques sont encore largement basées sur des normes établies dans les régions tempérées (ARC, 1984; INRA, 1989; NRC, 2007). Dans la publication 1, nous avons estimé des besoins énergétiques et protéiques d'entretien et de production pour les caprins, ovins et bovins en régions chaudes. Dans ce chapitre, l'objectif est de valider, avec une expérimentation, les besoins d'entretien et de croissance que nous avons estimés. Nous avons travaillé avec des moutons Black Belly et des chèvres Créole comme modèles biologiques bien adaptés à l'environnement chauds. En outre, les chèvres Créole ont une croissance plus faible et moins riche en lipides que les moutons Black Belly.

Effects of energy and protein levels and their interaction on nitrogen balance, the daily growth of Black belly lambs and Creole growing kids

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Summary

This study concerns Blackbelly sheep and Creole goats in Guadeloupe. The aim was to determine: 1) their energy and protein requirements for growth; 2) the effect of varying levels of both protein and energy and their interaction on animal growth, intake, digestibility and nitrogen balance. The energy requirements for maintenance (548 vs 484 kJ/kg LW^{0.75}) are higher for lambs compared to kids. Concerning the energy requirements for growth, 45 kJ/LW^{0.75}, the differences between the animal species are not significant (p=0.14). The protein requirements for maintenance (3.54 g DCP /kg LW^{0.75}) are similar for lambs and kids (p=0.86). The protein requirements for growth are 0.734 and 0.553 g/kg LW^{0.75} for lambs and kids respectively. Nitrogen excretion increases with nitrogen intake. The faecal nitrogen excretion is higher (p<0.01) in lambs compared to kids, whereas the opposite is recorded for urinary nitrogen. Nitrogen retention increases (p<0.01) with nitrogen intake, but lower increases are recorded for kids.

Keywords: Tropical kids, Tropical lambs, Energy requirements, Protein requirement, Nitrogen balance

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Introduction

Farming systems in humid tropical climates are generally quite different from those of temperate countries (Delgado *et al.*, 1999) because of the following factors: (1) relatively high temperature and humidity; (2) tropical C4 grass with low nutritive value diets compared to temperate C3 grass, even when eaten at a relatively young regrowth age; (3) livestock with low growth or milk production relative to the temperate genotype. However, the feeding recommendations in the tropics are still largely based on standards established in temperate regions (Agricultural Research Council (ARC), 1984; Institut National de la Recherche Agronomique (INRA), 1989; National Research Council (NRC), 2007). The adaptation to diet and climatic condition affects nutrient partition, animal growth, body composition and consequently, energy and protein requirements (Berg and Butterfield, 1976). The nutrient requirements of animals in tropical and warm regions could differ from those described in feeding standards for temperate countries. Blackbelly sheep and Creole goats are used in this study as two biological models well adapted to the tropical environment. Creole goats have weaker and thinner growth than Blackbelly sheep. The objective was to determine the effect of varying levels of both protein and energy and their interaction on animal growth, intake, digestibility and nitrogen balance. Moreover, the study establishes the energy and protein requirements for growth.

Material and methods

Experimental design, animals, housing and feeding

The animals were reared following European Union recommendations for animal welfare in accordance with the regulations of the Animal Care Committee of INRA. The study was conducted at the experimental animal station at the National Agronomic Research Institute (INRA) in the West Indies (Guadeloupe, latitude 16°16'N, longitude 61°30'W). The climate is humid tropical and the temperature ranges from 21°C to 31°C. Two sets of 24 Blackbelly lambs and two sets of 24 Creole kids were used during two successive trials. Each trial lasted 105 days and was organized as follows: three weeks of adaptation to diets; measurement of digestive balance over five days at 21-day intervals; weighing of animals at 21-day intervals. The first weighing and measurement of digestive balance took place at the end of the adaptation period.

The Blackbelly lambs and Creole kids were three months old at the beginning of each trial and the mean live weights were 27.3 ± 3.57 kg and 13.9 ± 2.69 kg respectively. All the animals were treated against external parasites on the first day of the adaptation period. The lambs and the kids lived in individual cages (2×2 m) with free-choice access to fresh water during all the experiments, except during the periods of digestive balance measurements for which they were in metabolic cages over a period of seven days (two days of adaptation to cages and five days of measurements).

For each trial, two animals of each species were randomly allocated to one of 12 diet treatments. The 12 diets were based on a combination of four energy levels (100, 125, 150 and 200% of theoretical energy requirements) and three levels of crude protein (CP) (7, 13 and 20% of CP content). The diets were formulated as indicated in Table 1. The objective was to have a large gradient of energy and protein. The diet formulations were combined in amounts designed to achieve the theoretical levels of energy and CP. The quantities offered were adjusted according to change in body weight every 21 days.

Growth, feed intake and total digestive tract measurements

The growth (average daily gain, ADG) of the animals was estimated by adjusting the weight curve using a linear model. Feed intake was calculated individually for each animal as the difference between the daily amounts of feed offered and feed refusal. Every three weeks for five consecutive days, the amounts of daily feed offered and refused, faeces output and urine excretion were collected and recorded for the animals in metabolic stalls. The urine was collected daily in drums containing sulphuric acid. The samples of faeces were stored at -20 °C before chemical analysis.

Chemical analyses of feeds, faeces and urine

The dry matter contents of forage, refusals and faeces were determined by drying at constant weight at 60 °C in a forced-draught oven. Samples for chemical analysis were dried under the same conditions. Diet and faeces samples were milled through a 1 mm screen (Reich hammer mill, Germany) prior to analysis. Organic matter (OM) and nitrogen (N) analyses were performed according to AOAC (1990) Methods 923.3 and 992.15, respectively, for OM and N. Dry lyophilized faecal samples were analysed for ash and N, and fresh samples of urine were analysed for N using the same methods as for the diets. CP was estimated as $N \times 6.25$.

Cell wall components (neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL)) in diet and excreta samples were determined as described by Van Soest *et al.* (1991) using a sequential procedure (AOAC, 2006, Methods 200.04 and 973.18, respectively, for NDF and ADF + ADL).

Calculations and statistical analysis

Metabolic energy intake (MEI/LW, kcal/kg LW) was predicted from digestible organic matter intake using the regression equation obtained from the 'RUMENER' database containing only calorimetric measurements on sheep, goats and cattle (Sauvant and Giger-Reverdin, unpublished):

$$\text{MEI/LW} = -2.03 + 4.03 \text{ DOMI/LW} \quad (n = 975, R^2 = 0.99, \text{r.s.d.} = 11.3)$$

The prediction is quite similar to that of NRC (2001) based on total digestive nutrients.

Some means were calculated before the statistical analysis to correct for daily biological variability and take into account the constraints of the methodological measures. Mean values corresponding to the five days of measurement were used for intakes, total tract digestion and N balance.

In a first step, data for the lambs and kids were analysed separately. Statistical analyses used the general linear model in Minitab 14. A fixed effects model was used for the trials (1df), the period (3df), the energy level (3df), the protein level (2df) and the interaction energy*protein level (6df). These fixed effects were tested for intake, total tract digestibility, nitrogen balance and ADG. The differences between the level effects were tested using Tukey's test.

In a second step, all the data were pooled to predict animal requirements and response to energy and protein inputs using the SAS (2008) general linear model. The general model was estimated as follows:

$$R_{ijkl} = \text{Specie}_i + \text{Diet}_j + \text{trial}_k + \text{period}_l + \alpha P$$

R_{ijkl} is the explained variable and αP is the random residual.

Diet was taken into account in the model as a random effect.

Digestible CP or metabolizable energy intake was introduced in the models as a covariable to study animal response to the protein and energy effects respectively. The ADG was used as a covariable to estimate the maintenance and growth requirements.

Table 1: Composition of diets

Ingredients	Low protein				Medium protein				High protein			
	LE	LE	ME	HE	LE	LE	ME	HE	LE	LE	ME	HE
Hay (% Dry Matter)	100	80	60	36	60	35	35	25	70	35	35	25
Banana	0	20	40	64	0	19.5	29.25	43.12	0	0	17.87	31.87
Flour												
Soya	0	0	0	0	0	0	9.49	15	19.6	19.63	29.19	27.38
Alfalfa	0	0	0	0	40	43.87	24.63	15	9.65	43.74	16.38	13.875
Premix	0	0	0	0	0	0.65	0.65	0.75	0.3	0.65	0.65	0.75
Bicalcium	0	0	0	0	0	0.325	0.325	0.375	0.15	0.325	0.325	0.375
Calcium	0	0	0	0	0	0.65	0.65	0.75	0.3	0.65	0.65	0.75
Urea	0	3	3	3	0	0	0	0	5	0	0	0
Chemical composition (% Dry Matter)												
Organic Matter	91.5	92.8	93.3	93.3	89.6	89.4	89.7	90.3	90.9	88.7	89.9	90.1
Crude Protein	9.6	7.6	6.7	7.1	12.8	11.8	13.2	15.0	18.7	20.7	21.5	19.4
Neutral Detergent Fibre	75.7	53.0	38.5	42	63.8	47.1	41.0	32.9	56.3	49.2	39.8	33.3
Acid Detergent Fibre	39.4	27.9	20.4	22.2	36.6	27.0	23.4	18.5	29.8	28.0	21.3	18.3

a Organic matter, b Crude protein, c Neutral detergent fibre with residual ash, d Acid detergent fibre, e Acid detergent lignin.

Results

Intake and total tract digestibility

Intake and total tract digestibility values are reported in Tables 2 and 3. There was a discrepancy between the experimental treatments as planned and observed. In particular, animals consuming the low nitrogen diets also had the lowest intakes of DM due to a significant rejection of pellets. Indeed, the rations containing banana flour are characterized by a low palatability. Except for low nitrogen diets, feed DM intakes varied widely as planned in the experimental protocol. Large variations in apparent total tract digestion of DM and its components were also recorded. Irrespective of animal species, the widest variations in digestion were recorded for protein.

Nitrogen balance

Urinary and faecal nitrogen excretions and nitrogen retention are reported in Tables 2 and 3. They increase significantly ($p < 0.01$) with nitrogen intake, as illustrated by the results for Equations 1 and 2 (Table 4). The faecal nitrogen excretion was significantly higher ($p < 0.01$) in lambs compared to kids, whereas the opposite was recorded for urinary nitrogen. Nitrogen retention increased ($p < 0.01$) with nitrogen intake, but lower increases were recorded for kids (Equation 3, Table 4). According to LW^{0.75}, the prediction equations for nitrogen balance are presented, as follows:

$$FN = 0.16 (\pm 0.093) + 0.3 (\pm 0.058) NI \quad (n=4, R^2=0.91, RSD=0.065)$$

$$UN = -0.0061 (\pm 0.085) + 0.31 (\pm 0.052) NI \quad (n=23, R^2=0.98, RSD=0.06)$$

$$RN = -0.34 (\pm 0.33) + 0.56 (\pm 0.38) NI - 0.036 (\pm 0.09) NI^2 \quad (n=24, R^2=0.95, RSD=0.11)$$

Growth and feed efficiencies

Growth values are reported in Tables 2 and 3. Growth increased significantly ($p < 0.01$) with the level of protein whatever the animal species. Negative to poor values were recorded with the low level of protein and the highest values for high protein inputs. Equations 6 and 7 (Table 4) quantify the positive effect of protein on growth. In contrast to the results for nitrogen retention, the rate of growth with protein input is higher for kids compared to lambs.

Irrespective of the animal species, growth also increased with the level of energy. Nevertheless, negative to poor growth was recorded for the low protein level. Equations 4 and 5 (Table 4) quantify the positive effect of energy on growth. There are no significant differences ($p=0.53$) between lambs and kids for rate for growth with energy input expressed on the basis of large weight. The rate of growth is higher ($p=0.03$) for kids when energy input is expressed on the basis of metabolic weight.

Feed efficiency values are reported in Tables 2 and 3. Feed efficiency increased in line with protein input.

Estimation of animal requirements

The estimation of energy and protein requirements for maintenance and growth are indicated in Table 4. Regardless of the basis of expression, i.e. energy requirement expressed on the basis of body weight or metabolic weight, there is little or no difference between animal species. Energy requirements for maintenance (548 vs 484 kJ/kg LW^{0.75}) are higher for lambs compared to kids when these are expressed on the basis of metabolic weight. There are no differences when requirements are expressed in live weight (236 kJ/kg LW). Concerning energy requirements for growth, at 45 kJ/LW^{0.75} or 23 kJ/kg LW the differences were not significant ($p=0.14$) between animal species. Whatever the mode of expression, the protein requirements for maintenance are similar (3.54 g/kg LW^{0.75} and 1.53 g/kg LW) for lambs and kids ($p=0.86$). The protein requirements for growth are 0.734 and 0.553 g/kg LW^{0.75} for lambs and kids respectively. These requirements for growth expressed as g/kg LW are 0.749 and 0.945 g for lambs and kids respectively.

Table 2: Growth performance, intake, apparent total tract digestibility and nitrogen balance of feeding diets of growing Blackbelly lambs discriminated by the input of energy and protein.

Parameters	Low protein				Medium protein				High protein				SEM	p-values		
	PE	LE	ME	HE	PE	LE	ME	HE	PE	LE	ME	HE		E	P	E*P
DMI g/kg LW	21.0d	22.3d	22.8cd	25.6c	32.4b	35.9a	35.9a	35.9a	32.2b	35.4a	35.4a	37.4a	0.605	0.000	0.000	0.08
CPI g/kg LW	1.43f	1.57f	2.00e	2.27 ^e	4.09d	4.20d	4.63c	5.37b	5.68b	7.28a	7.34a	7.16a	0.087	0.000	0.000	0.000
DMI	522.8 ^e	553.1de	586.9de	671.2d	943.8c	992.0abc	1024.2abc	1072.2abc	963.9bc	1093.9ab	1104.6a	985.6abc	28.11	0.000	0.000	0.001
OMI	487.9d	515.0cd	541.6cd	618.3c	847.8b	888.7ab	921.6ab	969.0a	878.1ab	971.2a	994.8a	888.3ab	25.51	0.000	0.000	0.003
CPI	35.9f	39.2f	51.9ef	59.5e	119.0d	115.7d	131.8d	160.1c	169.9bc	224.3a	229.0a	188.4b	4.07	0.000	0.000	0.000
NDFI	212.4f	247.9f	363.1de	440.6cd	609.8a	482.5bc	450.0c	363.5de	565.3a	543.5ab	464.8bc	338.7e	17.25	0.000	0.000	0.000
ADFI	112.8f	132.2f	193.4de	234.1cd	347.5a	203.9bc	254.5c	203.9de	300.5b	309.4ab	249.6c	186.3e	9.44	0.000	0.000	0.000
Digestibility (%)																
DM	63.8bc	63.5bc	65.0abc	63.2bc	57.5d	61.5cd	65.1abc	70.0a	67.5ab	61.3cd	69.7a	68.7ab	1.20	0.000	0.000	0.000
OM	64.6bc	64.3bc	66.1b	64.5bc	59.5c	64.3bc	67.7ab	72.7a	69.6ab	64.4bc	72.8a	71.7a	1.16	0.000	0.000	0.000
CP	15.9e	10.0e	35.0d	36.1a	54.9c	49.1c	53.6c	59.2bc	70.0ab	71.3ab	73.2a	67.2ab	2.58	0.000	0.000	0.000
NDF	67.8f	71.6cdef	78.8abc	82.1ab	75.4bcde	70.1def	70.6def	69.7def	82.6a	71.5cdef	76.5abcd	68.9ef	1.48	0.002	0.001	0.000
ADF	38.0d	47.9bcd	57.8ab	66.5a	57.2ab	47.7bcd	48.1bcd	46.0bcd	67.2a	50.0bcd	56.3abc	43.8cd	2.71	0.044	0.059	0.000
Nitrogen balance																
NI	5.7f	6.3f	8.3ef	9.5e	19.0d	18.5d	21.1d	25.6c	27.2bc	35.9a	36.6a	30.2b	0.65	0.000	0.000	0.000
FN	4.8d	5.5d	5.1d	6.1d	8.6bc	9.4abc	9.8abc	10.6a	8.1c	10.3ab	9.8abc	9.9abc	0.39	0.000	0.000	0.250
UN	1.1f	0.9f	1.6ef	1.5ef	3.7cd	3.1de	4.2cd	5.4c	8.9b	12.5a	11.9a	7.7b	0.40	0.000	0.000	0.000
RN	-0.1f	-0.1f	1.6f	1.9f	6.7e	6.0e	7.1de	9.6cd	10.2bc	13.1a	14.9a	12.6a	0.55	0.000	0.000	0.000
ADG	14.3ef	-0.40f	10.9ef	33.2e	114.5d	134.1bc	150.4ab	167.2a	114.5cd	132.0bc	168.8a	146.7ab	5.64	0.000	0.000	0.000
ADG/kgLW	0.5ef	-0.0f	0.4ef	1.2e	3.4d	5.0ab	5.5ab	5.7a	3.9cd	4.5bc	5.5ab	5.6a	0,22	0.000	0.000	0.000
IC	0.47ef	-0.02f	0.35ef	1.25e	3.42d	5.03ab	5.46ab	5.71a	3.89cd	4.53bc	5.51ab	5.60a	0.221	0.000	0.000	0.000
FE	0.022cd	-0.001d	0.008cd	0.045c	0.105b	0.140ab	0.151a	0.140a	0.120ab	0.126ab	0.155a	0.151a	0.0085	0.000	0.000	0.003

Table 3: Growth performance, intake, apparent total tract digestibility and nitrogen balance of feeding diets of growing Creole kids discriminated by the input of energy and protein.

Parameters	Low protein				Medium protein				High protein				p-values			
	PE	LE	ME	HE	PE	LE	ME	HE	PE	LE	ME	HE	SEM	E	P	E*P
DMI g /kg LW	19.9d	22.4d	23.3d	22.3d	34.6bc	38.8ab	36.2ab	40.5a	30.7c	40.5a	37.3ab	38.9a	0.92	0.000	0.000	0.000
CPI g /kg LW	1.95e	1.71e	1.54e	1.55e	4.53d	4.57d	4.94d	6.17c	6.00c	8.47a	8.30a	7.68b	0.123	0.000	0.000	0.000
DMI	288.4d	286.5d	275.3d	272.0d	546.4bc	618.1ab	570.6abc	641.1a	492.5c	622.3 ab	603.9ab	618.2ab	16.97	0.000	0.000	0.000
OMI	263.4d	266.0d	257.1d	253.6d	489.1bc	551.9ab	510.8abc	578.7a	446.7c	551.4ab	542.0ab	556.2ab	15.41	0.000	0.000	0.000
CPI	28.3d	21.9d	18.4d	19.5d	71.5c	74.3c	77.9c	97.9b	96.3b	130.6a	134.2a	121.9a	2.69	0.000	0.000	0.000
NDFI	218.5d	145.9c	98.8f	111.8ef	345.0a	282.9b	218.2d	204.1d	268.6bc	302.5b	228.0cd	197.4d	8.81	0.000	0.000	0.000
ADFI	115.0e	75.5f	53.0f	58.9f	198.5a	162.9bc	125.4de	114.6e	141.9cd	172.2b	122.2de	108.8e	4.92	0.000	0.000	0.000
Digestibility (%)																
DM	62.0abc	67.0a	69.2ab	61.7abc	54.6c	59.5bc	64.5ab	65.3ab	66.4ab	59.5bc	65.9ab	69.0a	1.86	0.001	0.002	0.000
OM	63.9bc	68.3ab	70.1ab	62.6bc	57.1c	62.9bc	67.5ab	68.5ab	68.8ab	62.6bc	69.3ab	72.2a	1.73	0.000	0.002	0.000
CP	36.4d	16.9e	18.5e	11.6e	50.0bcd	45.7cd	53.6abc	51.3bcd	68.7a	68.8a	68.9a	65.6ab	3.54	0.011	0.000	0.005
NDF	84.7a	79.5ab	73.5bc	73.3bc	72.5bc	66.8cd	65.2cd	62.9d	80.8a	70.0cd	72.0bcd	67.8cd	2.02	0.000	0.000	0.553
ADF	70.9a	60.5ab	49.7cd	49.2bcd	52.3bc	42.5cd	39.6cd	34.1d	63.6ab	47.5bcd	47.9bcd	41.3cd	3.66	0.000	0.000	0.784
Nitrogen balance																
NI	4.5d	3.5d	2.9d	3.1d	11.4c	11.9c	12.5c	15.7b	15.4b	20.9a	21.5a	19.5a	0.43	0.000	0.000	0.000
FN	2.9d	2.8d	2.3d	2.7d	5.7bc	6.5ab	5.8bc	7.5a	4.8c	6.5ab	6.7ab	6.7ab	0.35	0.001	0.000	0.004
UN	1.1e	0.8e	3.9bcde	0.9e	2.9de	2.8de	3.2cde	4.3abcde	6.8abcd	8.7a	7.8a	7.6abc	0.97	0.403	0.000	0.312
RN	0.5bc	-0.1bc	-3.3c	-0.5bc	2.8ab	2.6ab	3.5ab	3.9ab	3.8ab	5.7a	7.0a	5.5a	1.03	0.000	0.881	0.046
ADG	-2.0f	2.1f	-11.1f	-1f	49.9e	59.4de	67.2cde	100.4a	71.6bcd	83.8abc	89.7ab	93.8a	4.10	0.000	0.000	0.000
ADG/kgLW	-0.116d	0.164d	-0.864d	-0.148d	3.162c	3.632c	4.539bc	6.475a	4.582bc	5.492ab	5.780ab	6.075a	0.000	0.000	0.000	0.000
IC	-59.8b	68.1a	21.9a	-51.3b	12.2ab	13.1ab	10.0ab	7.0ab	6.4ab	7.0ab	8.4ab	7.1ab	6.9ab	0.306	0.001	0.000
FE	-0.013de	0.006d	-0.037e	-0.007de	0.092c	0.094c	0.121bc	0.160a	0.151ab	0.135ab	0.152ab	0.155ab	0.033	0.000	0.000	0.000

Table 4: Main equations for predictions of animal responses to diets and animal requirements.

Equation number	Prediction
1	$FN \text{ (g/d)} = E_i (\pm 0.463) + a_i (\pm 0.0176) \times NI \text{ (g/d)}$ <p>N=384, ETR=1.34, R²=80, p < 0.0001 E_i = 4.15 and 2.09 for lambs and kids respectively; a_i=0.231 and 0.306 for lambs and kids respectively</p>
2	$UN \text{ (g/d)} = E_i (\pm 0.7705) + 0.333(\pm 0.0271) \times NI \text{ (g/d)}$ <p>N=384, ETR=2.99, R²=59, p < 0.0001 E_i = -1.37 and +0.18 for lambs and kids respectively</p>
3	$RN \text{ (g/d)} = -2,444 (\pm 0.0207) + a_i (\pm 0.0207) \times NI \text{ (g/d)}$ <p>N=384, ETR=3.17, R²=71, p < 0.0001 a_i =0.4744 and 0.4019 for lambs and kids respectively</p>
4	$ADG \text{ (g/kg LW)} = -1.040(\pm 0.6684) + 0.01394 (\pm 0.0016) \times MEI \text{ (kJ/kg LW)}$ <p>N=384, ETR= 1.242, R²=81, p = 0.000</p>
5	$ADG \text{ (g/kg LW}^{0.75}) = -0.8188 (\pm 0.6794) + a_i (\pm 0.0007) \times MEI \text{ (kJ/kg LW}^{0.75})$ <p>N=384, ETR= 1.269, R²=80, p = 0.000 a_i =0.00151 and 0.00702 for lambs and kids respectively</p>
6	$ADG \text{ (g/kg LW)} = E_i(\pm 0.4151) + a_i (\pm 0.2565) \times DCPI \text{ (g/kg LW)}$ <p>N=192, ETR= 0.90, R²=89, p = 0.000 E_i = -0.1551 and -1.1565 for lambs and kids respectively; a_i=0.8818 and 0.9154 for lambs and kids respectively</p>
7	$ADG \text{ (g/kg LW}^{0.75}) = E_i(\pm 0.4568) + a_i (\pm 0.0364) \times DCPI \text{ (g/kg LW}^{0.75})$ <p>N=384, ETR= 1.25, R²=80, p = 0.000 E_i = 1.6281 and 0.7975 for lambs and kids respectively; a_i=0.2986 and 0.4509 for lambs and kids respectively</p>
8	$DCPI \text{ (g/kg LW}^{0.75}) = E_i(\pm 0.4568) + a_i (\pm 0.0364) \times ADG \text{ (g /kg LW}^{0.75})$ <p>N=384, ETR= 1.65, R²=86, p = 0.000 E_i = 1.621 and 0.7975 for lambs and kids respectively; a_i=0.2986 and 0.4509 for lambs and kids respectively</p>
9	$DCPI \text{ (g/kg LW)} = E_i(\pm 0.4396) + a_i (\pm 0.0733) \times ADG \text{ (g /kg LW)}$ <p>N=384, ETR= 0.762, R²=86, p = 0.000 E_i = 1.481 and 0.6628 for lambs and kids respectively; a_i=0.748 and 0.945 for lambs and kids respectively</p>
10	$MEI \text{ (kJ/kg LW}^{0.75}) = E_i (\pm 24.79) + 44.9 (\pm 4.19) \times ADG \text{ (g /kg LW}^{0.75})$ <p>N=384, ETR= 101.8, R²=73, p=0.000 E_i = 548.2 and 484.1 for lambs and kids respectively</p>
11	$MEI \text{ (kJ/kg LW)} = 236.2 (\pm 10.27) + 22.9 (\pm 1.86) \times ADG \text{ (g /kg LW)}$ <p>N=384, ETR= 48.3, R²=69, p=0.000</p>

Discussion

Intake and total tract digestibility

Apparent total tract digestion of DM and its components vary considerably according to diet composition. For both animal species, the variations in DM and OM with energy and CP input could be explained by the amounts of non-parietal components in diets (Nousiainen *et al.*, 2008). The low apparent total tract digestion of CP in the low protein diet could be explained by high nitrogen recycling linked to a low level of nutrition (Nolan and Leng, 1983; Moore *et al.*, 2004; Kebreab *et al.*, 2010).

Animal response

Our results concerning the impact of N intake on faecal nitrogen (FN) and urinary nitrogen (UN) is within the range of published results in the literature which, based on the analysis of a dataset from 25 studies, shows the slope of the linear relationship between NI and FN varying from 0.20 to 0.39 and the slope between NI and UN varying from 0.38 to 0.68 (Castillo *et al.*, 2000; Huhtanen *et al.*, 2008; Kebreab *et al.*, 2010; Weiss *et al.*, 2009). Our results are consistent with the mean values of 0.26 and 0.32 for faecal and urinary nitrogen, respectively, derived from a meta-analysis (Salah *et al.*, 2015). The corresponding values obtained in our studies were 0.26 for FN and 0.32 for UN.

Estimation of animal requirements

Our estimations of energy requirements for maintenance ($\text{Kj/LW}^{0.75}$) are similar to the values reported by Salah *et al.* (2014) in their meta-analysis. However, they did not report differences between sheep and goats, contrary to our results. Like Salah *et al.* (2014), we also recorded differences between animal species depending on the mode of expression of energy requirements ($\text{LW}^{0.75}$ versus LW), with no significant differences when the maintenance requirements were expressed on the basis of LW. Although our estimates of growth requirements are higher, they are also close to the predicted values of Salah *et al.* (2014). Like these authors, we did not find significant differences between animal species whichever the mode of expression of the result. Our estimates of the ME requirements for maintenance of Blackbelly lambs and Creole kids are close to those reported by Paul *et al.* (2003) for Indian sheep ($533 \text{ kJ/kg LW}^{0.75}$) and Mandal *et al.* (2005) and Luo *et al.* (2004) for goats (453 kJ/kg

LW^{0.75} and 487 kJ/kg LW^{0.75}, respectively). Moreover, our results of ME requirement for maintenance are higher than the values of 330, 350, 420 and 450 kJ/kg LW^{0.75} obtained for temperate growing sheep by AFRC,(1993); INRA, (1989), ARC, (1989), respectively. For goats, our results are slightly higher than the values of 425.8, 414.9 and 472.9 kJ/kg LW^{0.75} obtained by NRC, (2000); INRA, (1989) and Sahlu et al. (2004) for temperate growing genotypes. Tropical genotypes, such as Blackbelly sheep and Creole goats which are not generally selected for muscle deposition, tend to be fatter than temperate genotypes and consequently the energy cost of LW gain is higher (Early *et al.*, 2001). Our results illustrate this last observation. Our estimations for ME requirements for growth are higher than the values obtained for tropical genotypes (19.48 and 24.3 kJ/g gain for sheep and 24.3 and 24.31 kJ/g gain for goats) reported by Paul et al. (2004), Salah et al. (2014) and Mandal et al. (2005), respectively. Moreover, the value of 45 kJ/g gain obtained in this study is higher than the values of 20.6 and 18.01 for sheep and 30.3 and 26.0 kJ/ g gain for goats by NRC, (1989); ARC, (1989); NRC, (2000) and AFRC, (1998), respectively.

Our estimations of CP requirements for maintenance (DCPI/LW^{0.75}) are also similar to the values reported by Salah *et al.* (2014) in their meta-analysis. However, unlike these authors, we did not find significant differences between animal species when the basis of expression was LW^{0.75} contrary to our results expressed on the basis of LW. Moreover, our results are slightly higher than the values obtained for temperate genotypes (3.2; 3.2 and 2.16 g DCP/ kg LW^{0.75} for sheep and 2.82 and 2.13 g DCP/ kg LW^{0.75} for goats) by NRC. (1981; 1985), Swidish system. (1995) and INRA. (1989), respectively. Our estimations of DCP requirements for growth (DCPI/LW^{0.75}) are in the order of two times higher than those reported by Salah *et al.* (2014) in their meta-analysis. The protein requirement for gain is estimated at 0.30 g DCP/g gain by Salah *et al.* (2014), but it is curvilinear depending on animal growth (from 0.44 when ADG is close to 0 to 0.206 when ADG is 20 g/kg LW^{0.75}). Globally, our estimates in this experiment are higher than the previously published estimates for temperate ruminants (INRA, 1989: 0.26 gDCP/ g gain for sheep and NRC, 1981: 0.20 gDCP/g gain). These results could partly be explained by leaner body growth in temperate genotypes. Our estimates fall outside the published range for tropical ruminant livestock, that is, 0.26 to 0.31, 0.17 to 0.34 and 0.19 to 0.45 for sheep, goat and cattle, respectively (Salah *et al.*, 2014).

Conclusions

This work establishes the energy and protein requirements for the maintenance and growth of Creole kids and Blackbelly lambs. These requirements are consistent with the information already published for animals. There are no or only small differences between kids and lambs.

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PUBLICATION 4

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Adaptation du système Français INRA pour évaluer la valeur nutritive des fourrages tropicaux

Dans les régions chaudes, l'apport d'énergie et de protéines se fait principalement avec les fourrages et les ressources non-conventionnelles qui subissent d'importantes fluctuations saisonnières tant quantitatives que qualitatives (Leng, 1990). La caractérisation de ces ressources est un important enjeu. Il y a peu d'informations disponibles concernant l'ingestibilité, la valeur énergétique (énergie métabolisable ou l'énergie nette) et la valeur protéique (protéines métabolisables) pour de nombreux aliments non-conventionnels.

Pour prédire avec précision la valeur des aliments des régions tempérées, différents modèles et équations basés sur de nombreuses données expérimentales de consommation et de digestion ont été développés (Sauvant et Nozière, 2013; NRC, 2007). L'information est plus rare avec les fourrages des régions chaudes.

De très nombreuses caractérisations chimiques de ces ressources ont été réalisées dans de nombreuses régions au cours de ces dernières années (site Internet "Feedipedia" consultable à partir du lien <http://www.feedipedia.org/>). Des tables de valeur alimentaire ont été publiées, mais les équations utilisées ne sont pas spécifiques aux ressources de ces régions.

L'ingestibilité des fourrages est un critère important qui doit être apprécié à travers des bases de données spécifiques aux régions chaudes, compte tenu des spécificités de ces ressources très riches en parois végétales. Leurs valeurs énergétiques et protéiques sont aussi à préciser. L'ingestibilité des fourrages des régions chaudes, critère important et spécifique de ces ressources très riches en parois végétales, doit être renseignée par les bases de données. Elles doivent aussi préciser leurs valeurs énergétiques et protéiques.

Dans ce chapitre, notre objectif est d'évaluer le potentiel du système d'alimentation INRA en cours de révision (Sauvant et Nozière, 2013) en mobilisant des bases de données spécifiques aux ressources des régions chaudes.

Adaptation of the French unit system to evaluate the feed values of tropical and warm roughage.

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ABSTRACT

The aim of this study was to predict energy and protein values of tropical forages as well as their fill units using meta-analysis approach. The suggested fill unit of reference tropical forage corresponds to an ingestibility of 75, 55 and 84g/kg LW^{0.75} and digestibility of 60.0, 65.9 and 60.9% for sheep, goats and cattle, respectively with a chemical composition of 14.0% CP, 73.1% NDF and 39.3% ADF. Nitrogen values were expressed in term of protein digestible in the intestine (PDI) that is necessitating the estimation of dietary protein degradable in the rumen, the amount of microbial protein that could be synthesized from the energy available in the rumen, when degraded N are not limiting (PDIME) and the amount of microbial protein that could be synthesized from the degraded N, when energy are not limiting (PDIMN). Their determination is based on the estimation of effective degradability of nitrogen (ED_N), true digestibility of dietary protein in the small intestine (drN) and microbial nitrogen flow (N_μ). statistical analysis indicated that the effective degradability of nitrogen (ED_N) obtained via in sacco method varied significantly and curvilinearly with CP content and was negatively correlated to NDF content without any significant difference between leaves, legumes and grass (P>0.2). The statistical analysis indicated that N_μ is closely correlated to organic matter fermented in the rumen (FOM) with a production of 22.99 gN_μ/kgFOM. The mean value of drN obtained in our study is 67.07%. In the absence of measured data, drN can be predicted from CP and NDF content with a high coefficient of prediction. The mean value of PDIA obtained in this study for tropical forages was 23.19 g/kg DM and it was lower than the mean value (35.83 g/kg DM) obtained via the application of the predictive equation of INRA (2007). The predicted value of PDIA by INRA method varied from 15.26 to 36.54 g/kg DM. The value of PDIA obtained by nitrogen flow method varied

from 10.99 to 36.37 g/kg DM. The predicted value of PDIN by INRA method varied from 36.40 to 79.39 g/kg DM. The value of PDIN by nitrogen flow method varied from 29.04 to 65.03 g/kg DM. The predicted value of PDIE by INRA method varied from 68.01 to 89.08 g/kg DM. The value of PDIE by nitrogen flow method varied from 29.0 to 84.34 g/kg DM.

Keywords: tropical roughage, fill unit, energy, protein

Introduction

In tropical and warm environments, most of energy and protein intake derived from forages and unconventional resources that undergo large seasonal fluctuations in both quantity and quality. Their adequate characterization is the basis for their rational use in the feeding systems (Minson, 1990). For many unconventional tropical feeds, there is insufficient information available regarding their ingestibility (fill unit), energy content (metabolisable energy or net energy) and protein values (metabolisable protein) compared to temperate feedstuffs. Indeed, the majority of farmers in tropical countries use temperate feeding standards which are often misleading in formulating rations for ruminants in developing countries (Preston and Leng, 1980). It appears that, knowledge of their ingestibility and chemical composition (energy and protein) constitute an important step for both the appreciation of their nutritive value and the coverage of animal requirements to develop specific tropical feeding standards.

Compared to temperate resources for which various models and equations based on numerous experimental data of intake and digestion have been developed (INRA, 2007; Sauvant and Nozière, 2013; NRC, 2007), specific data on tropical forages are scarce and necessitate more precision. For this last ones, some old tables of chemical composition has been established us the Latin American Feed Tables of NcDowell et al. (1974), FAO tropical feeds based on the work of Bo Göhl (1991) and those presented in INRA (1989). Moreover some new systems have published values for warm and tropical feedstuffs (Amrita, 2012), but the major used parameters are extrapolations from standards obtained with temperate feeds. NRC (2007) and the website “Feedipedia” (<http://www.feedipedia.org/>) open since the end of 2012, offered numerous information on chemical composition and nutritive values of tropical feedstuffs. This information could be improved by a more systematic and more homogeneous use of relationships and equations specific of these type of products.

Moreover, given the importance of cell wall components of forages warm regions, it was not sure if their ingestibility, energetic and protein values can be related to their chemical

composition by the same equations as those used for forage in temperate zones especially for grazing (Richard et al., 1990). It is therefore important to know the value of forages in different ecotypes in order to characterize them under tropical conditions.

The objective of this paper was 1) to predict the fill unit (FU), net energy (NE) or metabolizable energy (ME), protein digested in the intestine when rumen-fermentable energy is limiting (PDIE) and protein digestible in the intestine when rumen-fermentable nitrogen is limiting (PDIN) of the French feed unit INRA system as described by Sauvant and Nozière (2013); 2) to propose, if necessary, some adaptations in this system to lead to a better evaluation.

Materials and methods

Data collection

Data collection has two objectives : 1) to validate or not equation of prediction of feed value based on temperate data; 2) to build, if it is necessary, specific equations based on tropical forages. To compare our results with those obtained by INRA, we used the same unit for energy (Kcal) and protein (g/kg DM).

A literature database was performed with published results coming from international scientific publications, reviews, reports, books, thesis... Search was conducted using public data search generator such as science en direct, Web of Science, CAB abstract, Pubmed, google scholar and by using different keywords on ruminants feeding and nutrition. The structuration of this dataset is summarized by the figure 1. Four types of trials focused on the following points have been selected and pooled: intake and total tract digestibility; energy balance in calorimetric chamber; in sacco degradability in the rumen; duodenal and intestinal nutrient flows. At a minimum, trials must report information on diet chemical composition as dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), level of intake, and digestibility.

In total, 321 publications representing 1383 different treatments were pooled to be used in the present study: 174 publications with 690 treatments on tropical forages distributed alone and ad libitum containing information on ingestibility and digestibility were used to estimate FU. 21 publications only for tropical forages (76 treatments) based on calorimetric chamber were used to predict energy values, 100 publications for tropical resources (559 treatments) were used to predict effective degradability of nitrogen in sacco (ED_N) and 26 publications for

tropical forages (58 treatments) with measurements of nitrogen flows were used to estimate digestibility of N in intestine (drN) and microbial N production in the rumen (N μ).

Estimations, calculations and encoding

Some estimates were applied when data were lacking in the publications and when the good predictors for calculations were available as chemical composition of diet. Thus, the OM content of diet and the OM digestibility were estimated as DM multiplied by 0.9 and DM digestibility multiplied by 1.05, respectively, according to mean values of feed tables of tropical countries. Publications were systematically coded. The main encoded criteria were animal species (sheep, goats and cattle) and roughage type (grass, legume, foliage, straw...). All animals introduced in the database are growing. Moreover, specific coding has been performed in order to identify publications in which a minimum variation on each explanatory variable (X) was observed (Sauvant et al, 2005). Therefore, the minimum variation of X (ΔX_{min}) was determined as follows:

$$\Delta X_{min} = \mu (\Delta X_{ij}) - |2 \times SD \Delta X|$$

$$\Delta X_{min} = |X_{\text{treatment I}} - X_{\text{treatment j}}| \text{ and } SD \Delta X = SD \text{ of } \Delta X_{ij}.$$

Thus, variations considered relevant when the variation of CP, NDF and OMd% between treatment within experiment was greater than 5%, 10% and 5%, respectively.

To be consistent with the INRA feed evaluation system which has undergone a recent revisions (Sauvant and Nozière, 2013), we used the same steps indicated below. Moreover, we also offer new specific predictions for tropical forages when there was no predictors or information used by the INRA system. The most important parameters used to calculate PDIA, PDIN and PDIE are in sacco degradability of nitrogen (ED_N), the true digestibility of nitrogen in the intestine (drN) and microbial protein (N_{mic}) which vary according to fermented organic matter in the rumen (FOM). FOM can be calculated via the different variables of the digestible organic matter in total tract (MOD g/kg DM), dietary protein undegradable in the rumen and digestible in the small intestine (PDIA g/kg DM), starch digestible in the intestine (StarchDint g/kg DM), fatty acid digestible in the intestine (FADint g/kg DM), neutral detergent fiber digestible in the intestine (NDFDint g/kg DM) and products in fermentation in silage (PF). FADint is derived from duodenal fatty acid (FA_{duo} g/kg DM) and ether extracts (EE g/kg DM).

FOM (g/kgDM) = MOD – PDIA – StarchDint – FADint – NDFDint – PF (Sauvant and Nozière, 2013)

$$FA = 0.95 \times EE \text{ for hay (Sauvant and Nozière, 2013)}$$

$$FA = 0.75 \times EE \text{ for silage and green forages (Sauvant and Nozière, 2013)}$$

$$FA_{duo} = 9.6 + 0.75 FA \text{ (Sauvant and Nozière, 2013)}$$

$$FAD_{int} = 6 + 0.599 FA_{duo} \text{ (Sauvant and Nozière, 2013)}$$

In our study we used the same previous equations to calculate FOM. Nevertheless, we fixed a mean value of 10 g/kg DM of EE used to calculate FADint obtained from Indian feed tables containing more than 280 types of tropical roughages (Amrita, 2012). However, we neglected the value of starch.

$$PIA \text{ (g/kg DM)} = CP \text{ (g/kg DM)} \times (1-0.01) \times ED_N \quad \text{(Sauvant and Nozière, 2013)}$$

$$PDIA \text{ (g/kg DM)} = PIA \text{ (g /kg DM)} \times 0.01 \times drNdiet \% \quad \text{(Sauvant and Nozière, 2013)}$$

$$ED_N = a + (b \times c) / (c + kp \%)$$

Where a is the washing loss representing the soluble N fraction, b is the insoluble but slowly degradable N fraction, c is the rate of degradation of fraction b, kp is the rumen outflow rate. In our study we used the prediction equation derived from the data base of Assoumaya et al. (2007) which includes sheep, goats and cattle to predict kp to prevent the use of a fixed values of 6% in the French and Scandinavian System or 4.5% in the Dutch System and because ED_N depends on the chemical composition as indicated below:

$$Kp (\%) = 4.08 - 0.019 NDF + 0.039 CP \text{ (n = 536, nexp = 183, RSD = 0.51)}$$

$$Kp (\%) = 5.27 - 0.031 NDF \text{ (n = 536, nexp = 183, RSD = 0.51)}$$

$$Kp (\%) = 2.36 + 0.039 CP \text{ (n = 634, nexp = 229, RSD = 0.52).}$$

$$PIME \text{ (g/kg DM)} = 0.8 \times 6.25 \times N_{mic} \text{ (g/kg MS)}$$

The value 0.8 is used because it is assumed that 80% of microbial nitrogen is in the form of true protein.

$$PDIME = 0.8 \times PIME$$

$$PDIE = PDIA + PDIME$$

$$PIMN = 0.8 (CP \times 0.01 \times ED_N)$$

$$PDIMN = 0.8 \times PIMN$$

$$PDIN = PDIA + PDIMN$$

Statistical analyses

These meta-analyses were performed following the recommendations of Sauvant et al. (2008) using Minitab software (Minitab® 15.1.30.0., 2007). Several models were used depending on the objective.

For fill unit, the model is presented as follow:

$$Y_{ij} = B_0 + EXP_i + B_1 X_{ij} + B_2 X_{ij}^2 + e_{ij}$$

Y_{ij} is the explained variable (VDMI or OMd), B_0 is the intercept, EXP_i is the effect of experiments on the intercept, B_1 is the coefficient of linear regression of the covariables (CP, NDF and ADF), B_2 is the coefficient of quadratic effect of the covariables, and e_{ij} is the residuals.

For effective degradability of nitrogen, the model is presented as follow:

$$Y_{ij} = B_0 + EXP_i + FOR_i + B_1 X_{ij} + B_2 X_{ij}^2 + B_i X_{ij} + e_{ij}$$

Y_{ij} is the explained variable (ED_N), B_0 is the intercept, EXP_i is the effect of experiments, FOR_i is the effect of forage class (leaves, legumes of grass) on the intercept, B_1 is the coefficient of linear regression of the covariables (CP or NDF), B_2 is the coefficient of quadratic effect of the covariables, B_i is the effect of the interaction between forage class and covariable on the slope and e_{ij} is the residuals.

For energetic value, the model is presented as follow:

$$Y_{ij} = B_0 + EXP_i + B_1 X_{ij} + B_2 X_{ij}^2 + e_{ij}$$

Y_{ij} is the explained variable (GE, DE, UE, ECH₄, ME), B_0 is the intercept, EXP_i is the effect of experiments on the intercept, B_1 is the coefficient of linear regression of the covariables (CP or NDF or OMd...), B_2 is the coefficient of quadratic effect of the covariables, and e_{ij} is the residuals.

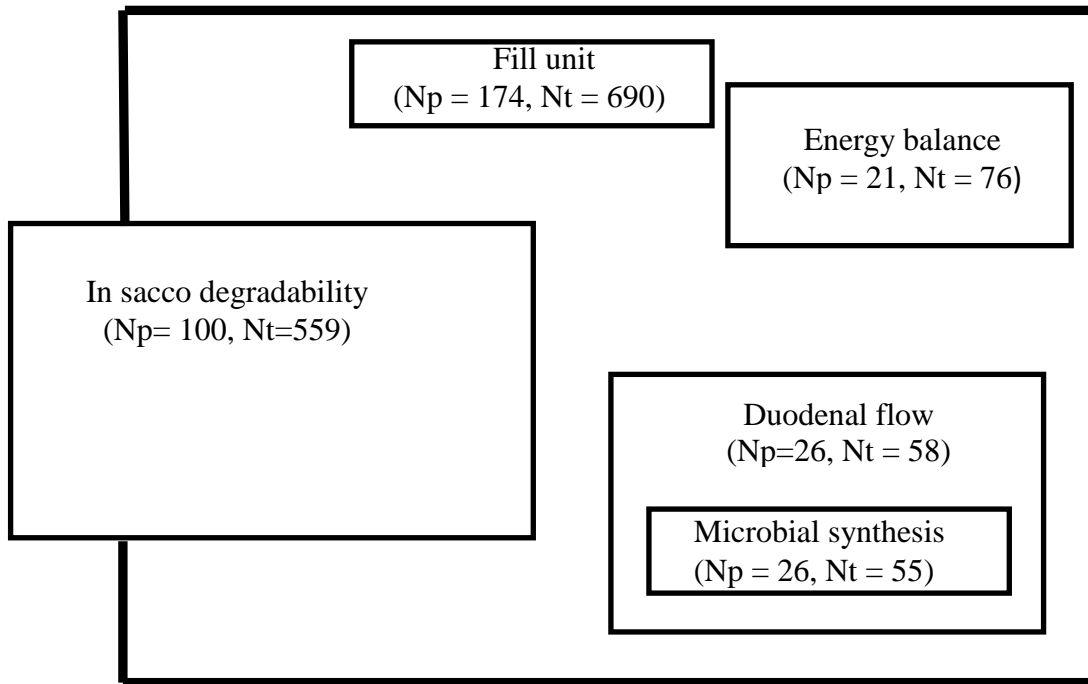


Figure 1: Structuration of database (Np: number of publications, Nt: number of treatments)

Results

Presentation and Description of datasets

The different equations obtained in this study for energetic and protein values were presented in Table 2 and 3. Each equation was compared with equation established previously if possible. The comparative equations obtained previously in the literature either for tropical or temperate forages were presented in italics and bold.

The characteristic of the databases used for the estimate of the parameters are indicated in the table 1. Only data on tropical forages distributed alone and ad libitum was described. The data indicated large variations in CP and NDF contents that are constitute the limiting nutritional factors under tropical and warm conditions. The values of CP and NDF concentration of forages suggests that low to good quality roughages were included in the dataset (Table 1).

Table 1: Characteristics of the variables of the database used for tropical roughages.

Item	N	Mean	SD	Minimum	Maximum
<i>Fill Unit</i>					
CP%DM	690	9.7	4.31	2.2	26.3
NDF%DM	517	68.0	9.15	40.1	92.2
MO%DM	571	90.6	3.37	69.9	98.8
OMd%	605	58.7	8.85	33.7	93.2
DMI/LW ^{0.75}	690	61.1	20.13	22.0	149.4
<i>PDI</i>					
CP%DM	53	8.6	4.53	2.3	23.1
NDF%DM	49	67.3	11.22	46.2	89.8
Nduo%DMI	50	1.87	0.87	1.0	5.4
N μ %DMI	50	1.05	0.42	0.27	2.12
OMduo%DMI	71	51.9	7.75	34.0	72.9
<i>In sacco degradability</i>					
CP%DM	378	15.8	6.44	3.0	32.1
NDF%DM	332	49.6	12.44	26.2	85.1
Kp	322	0.038	0.0053	0.026	0.058
ED _N %	303	55.6	16.9	17.95	90.7
<i>Energy</i>					
CP g/kgDM	71	112.5	43.77	24.0	224.4
NDF g/kgDM	56	593.0	95.2	348.0	753.0
MO g/kgDM	68	892.6	45.50	730.0	953.0
GE kcal/kgDM	59	4263.1	180.00	3811.1	4603.9
DE kcal/kg DM	73	2527.9	498.30	1764.2	3756.0
ME kcal/kg DM	58	2084.9	453.50	1229.6	3349.3

n= number of observation; CP%DM= crude protein content; NDF%DM= neutral detergent fiber content; MO%DM= organic matter content; OMd%= organic matter digestibility; DMI/LW^{0.75}= dry matter intake per metabolic live weight; PDI= protein digestible in the intestine; Nduo= duodenal nitrogen; OMduo= duodenal organic matter; N μ = microbial nitrogen; OM μ = microbial organic matter; NI= nitrogen intake; Kp= passage rate; ED_N= effective degradability of nitrogen; GE= gross energy; DE= digestible energy; ME= metabolisable energy.

Fill Unit

The objective of any nutritional system is to maximize the utilization of forages and minimize the utilization of concentrate. To formulate rations, we have to know the feed capacity of animal that depends on forage ingestibility and the ingestibility of forage that depends on animal capacity. For this reason a common system of Fill unit (FU) has been elaborated in relation with the regulatory mechanisms of intake which simultaneously gives a single value of feed intake for each food and a single value of the intake capacity for each animal category (INRA, 1978). In the previous INRA editions of tropical forages it was suggested to define the level of DMI of the standard sheep at 60 (humid conditions) or 65 (dry conditions) g/LW^{0.75} as fill unit (Xandé et al., 1989). However, the value of 75 g/LW^{0.75} has also been proposed by Aumont et al. (1991) for tropical forages. In this study, we used the INRA, URZ database (1992) containing about 130 data for which one Fill Unit (FU) corresponded to a voluntary dry matter intake (VDMI) of 75g/kgLW^{0.75} by adult rams fed ad libitum. This intake corresponded to a very early regrowth and fertilized forage (14 to 21 days of regrowth). The statistical analysis of CP, NDF, ADF content of this forages against VDMI indicated that the characteristics of this forage at the level of 75g/kg LW^{0.75} are as follow: 14% CP, 73.1% NDF and 39.3% ADF. Using a larger data base compiled from the literature (Figure 1), VDMI corresponding to the reference grass have been predicted by the regression of VDMI against CP, NDF and ADF content. The intra-publication statistical analysis indicated that at the same chemical composition (14% CP, 73.1% NDF and 39.3% ADF), VDMI estimated for this reference grass was equal to 75, 72.09 and 88.41 g/kg LW^{0.75}, respectively for sheep, goats and cattle.

With the assumption that the digestibility of the organic matter (OMd) may be different among the three animal species for the same forage, the statistical analysis of OMd against the corresponding VDMI for each specie indicated that OMd of the reference forage was equal to 60.0, 65.9 and 60.9% for sheep, goats and cattle, respectively (Figure 2).

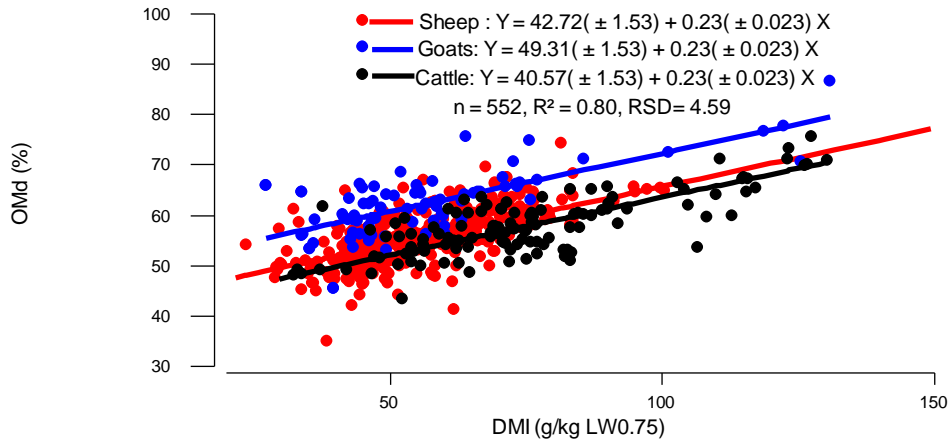


Figure 2: Relationship between DMI and OMd

Prediction of energy content of tropical forages

Gross energy (GE)

The range of variation of GE is indicated in Table 1. GE is closely related to the CP content of the forage with linear positive pattern as shown in equation 1 (Table 2). The RSD of this equation is larger than the corresponding equations previously proposed for temperate (n°2) and tropical (n°3) forages. This is likely the outcome of the diversity of the origins of the treated data. The intercepts as the slopes of equations 2 and 3 are not statistically different from those of equation 1. It can be concluded that equations 1 to 3 are not significantly different. Due to the negative relationship associating forage NDF and CP contents, GE content was also linearly and negatively correlated to NDF content as indicated in equation 4 (Table 2). However the level of accuracy of this equation is very poor. It can be concluded that it's possible to use the equation established for temperate forages with a larger number of data to estimate GE content of tropical forages.

Energy digestibility (Ed%) and Digestible energy DE

As it has been frequently observed, Ed% is closely linked with OMd % which depends first on the chemical composition of diets (Figure 3, equation 5, Table 2). The comparative equations using the same predictor (OMd) was presented for temperate (n°6) and tropical (n°7) forages (Table 2). Regression 5 presents the same accuracy than the 7 one already

proposed for tropical green forages, however they are both less accurate than the n°6 proposed for temperate green forages. A simulation of data provided by equations 5, 6 and 7 for same values of OMD% shows that the results of the 3 data sets are very similar and did not differ statistically. When data on total tract organic matter digestibility (TTOMd) are not available, Ed% can be predicted with CP and NDF content however the accuracy of these predictions are very poor compared to that of equations 5 to 7 (Table 2, equation 8 and 9).

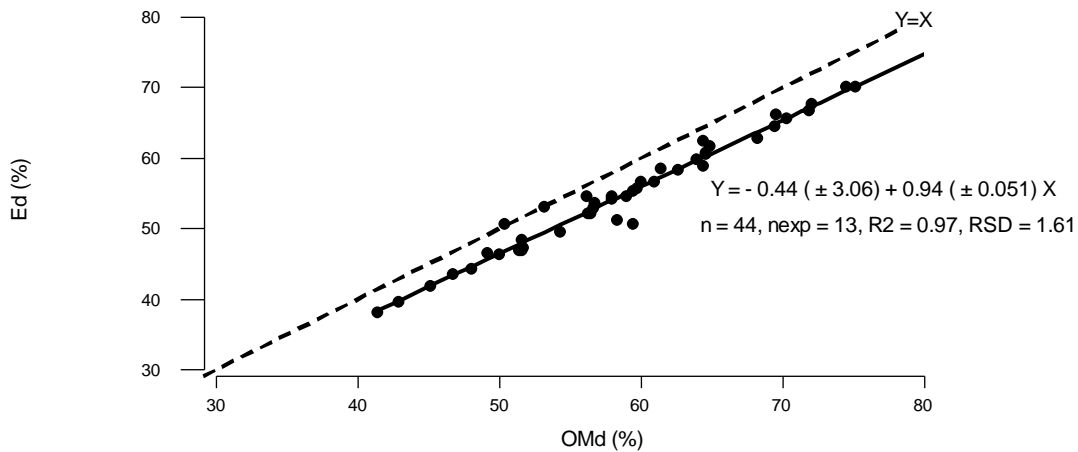


Figure 3: Relation between OMD and energy digestibility (Ed%)

Metabolizable energy (ME)

The range of variation of ME is shown in table 1. ME is the difference between DE and the energy lost in the urine (UE) and methane (E_{CH₄}) that partly depend on the chemical composition of the diets (Table 2, equations 10, 12, and 14). The equation n° 10 used to predict UE%GE is not statistically different from equation n° 11 (Table 2) proposed for a large range of diets which are mostly based on temperate feed. The comparative equations for CH₄ emission (g/kgDM) were presented in equation 12 and 13 (Table 2). The equation 12 obtained with 41 tropical forages is very similar to the equation 15 calculated from 283 forages, mostly temperate ones.

Table 2: Linear and multiple prediction equations for energy content of tropical forages obtained in this study and previous studies.

N° Equation	Equation	n	R ²	RSD
1	GE (kcal/kg OM) = 4482.53(±36.96) + 1.47 (± 0.29) CP g/kg OM	43	0.88	69.0
2	INRA, 1989 for temperate forage GE (kcal/kg OM) = 4531 + Δ + 1.735 CP g/kg OM With Δ = +82, - 11, - 71 for green alfalfa, red clover and green grass	166	0.94	38.0
3	INRA, 1989 for tropical forage GE (kcal/kg OM) = 4543 + 2.01 CP g/kg OM	16	0.93	32.8
4	GE (kcal/kg DM) = 4697.6 (±159.0) -0.72 (± 0.27) NDF g/kg DM	38	0.87	75.4
5	Present equation for tropical forages Ed% = - 0.44 (± 3.06) + 0.94 (± 0.05) dMO%	44	0.98	1.6
6	INRA, 1989 for temperate green forages Ed% = - 0.068 + 0.957 OMd%	81	0.99	0.6
7	INRA, 1989 for 29 tropical forages Ed% = - 0.03 + 0.983 OMd%	29	0.96	1.5
8	Ed (%) = 50.07(± 2.85) + 0.073(± 0.023) CP g/kg DM	71	0.80	5.90
9	Ed (%) = 65.83 (± 5.97) - 0.012 (± 0.0099) NDF g/kg DM	57	0.70	5.84
10	Present estimation for tropical forages UE%GE = 1.74 (± 0.62) + 0.017 (± 0.0051) CP g/kg DM	60	0.74	0.93
11	INRA, 2013 for various diets, mainly temperate UE%GE = 1.34 + 0.019 CP g/kg DM	411		0.59
12	Present prediction for tropical forages CH ₄ g/kgDM = - 15.36 (±12.42) - 1.63 (± 0.82) DMI%LW + 0.13 (±0.04) MOD - 0.0001 (±0.00004) MOD ²	41	0.91	2.03
13	Sauvant et al, 2011 for forages (mostly temperate) CH ₄ g/kgDM = - 22.4 - 2.25 DMI%LW + 0.137 MOD - 0.0009 MOD ²	283		1.6
14	ME/DE = 0.82 (± 0.018) - 0.000064 (± 0.00015) CP g/kg DM	56	0.80	0.02
15	ME/DE = 0.81 (± 0.036) - 0.00002 (± 0.000062) NDF g/kg DM	42	0.76	0.02

GE= gross energy; Ed= energy digestibility; OMd= organic matter digestibility; UE= urinary energy; CH₄= energy in methane; DE= digestible energy; ME= metabolisable energy; MOD= digestible organic matter; MOD= digestible organic matter.

Prediction of Intestinal Digestible Protein (PDI)

Effective degradability of nitrogen (ED_N)

The level of ED_N estimated with the reference method of *in sacco* degradation (Doreau and Aufrère, 1990) varied largely: from 17.9 to 90.7% with a mean value of 55.6% in the database (n=297). A low variation was observed with legumes class (n= 19; ED_N from 47.9 to 81.3% followed by forages (n= 131; ED_N from 21.5 to 87.7%) and leaves (n= 147; ED_N from 17.9 to 90.7%). In the absence of direct measurements, ED_N of roughage can be predicted with an approximation on the basis of the feed chemical composition. The intra-publication statistical

analysis indicates that ED_N quadratically ($P < 0.05$) increases with CP content (Figure 4) without any significant differences between leaves, legumes and forage neither for the intercept ($P = 0.28$), or for the slope ($P = 0.25$). For temperate green forages a similar type of regression has been proposed (Baumont et al., 2007), the coefficient's values of this equation are closed however it was more accurate. This difference might be due to the diversity of the origin of the present database. As NDF and CP contents are negatively linked, it is logical that ED_N decreases with NDF content (Figure 5) without any significant difference between leaves, legumes and forages neither for the intercept ($P = 0.36$), nor for the slope ($P = 0.82$). The prediction is improved when CP and NDF were introduced in the same model as indicated with the following intra-publication generic regressions (equation 1, Table 3)

We don't found any differences ($P > 0.05$) between forage type (green, silage, hay and straw), may be because the low number of data for silage (6%), for hay (9%) and straw (4%). Unfortunately, the data included in this database don't contain information on age of regrowth.

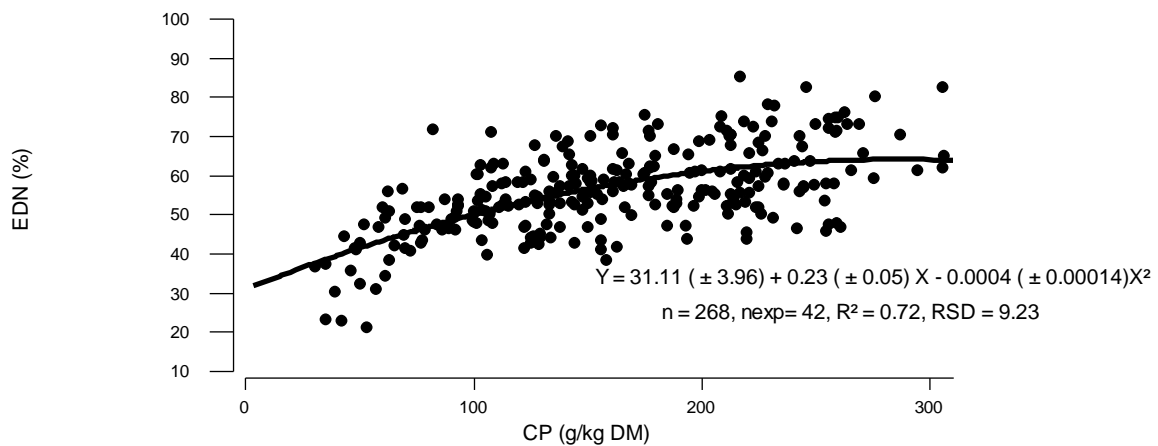


Figure 4: Effect of CP%DM of effective degradability of nitrogen.

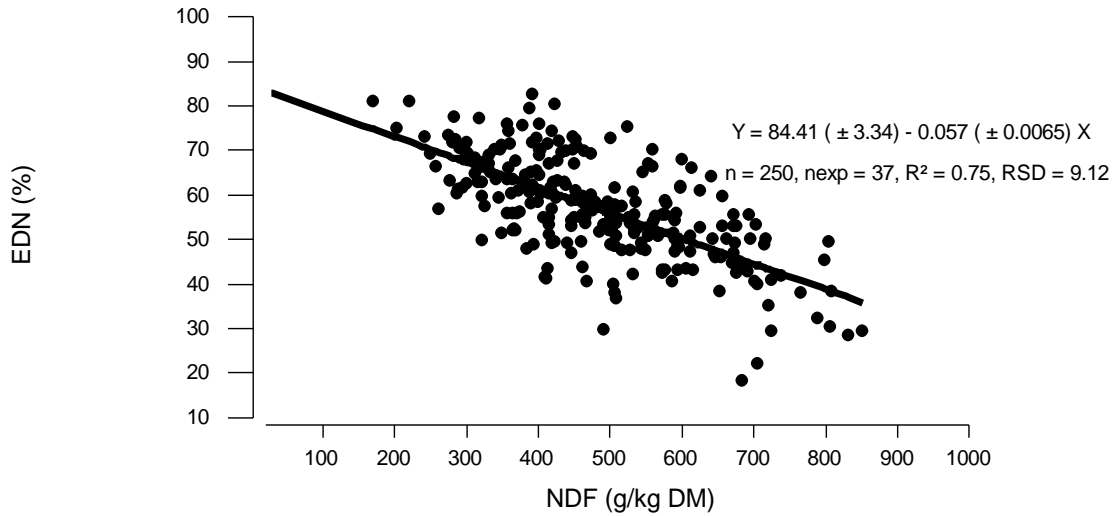


Figure 5: Effect of NDF of effective degradability of nitrogen.

Microbial duodenal nitrogen flow ($N\mu$)

The intra-publication statistical analysis showed a high positive relationship between microbial crude protein ($CP\mu$) and FOM. For each 1 unit increase in FOM, $CP\mu$ is increased by 0.062 g/kg DM. The mean value of microbial efficiencies was 135 $CP\mu$ /kg FOM (equation 2, table 3). The comparative equation (eq 3, table 3) obtained from data of the literature is very similar and there was no difference between the intercept and slope of equations 2 and 3 (Table 3).

True digestibility of dietary protein in the small intestine (drN)

The reference method used by INRA system for the prediction of intestinal digestibility of undegradable protein is based on the use of the technique of mobile bags in the intestine (Sauvant and Nozière, 2013). To our knowledge, compared to temperate resources for which this method is used, data on tropical resources are limited. The mean value of drN obtained with measured data in this study tends to be lower ($p=0.14$) with C4 grass compared with C3 grass (67.07% vs 72.75%). Consequently the main value of 67.1 is recommended for the CP intestinal digestion of C4 grass. Statistical analysis indicated that the intestinal digestion of CP decreases with the NDF content and that the addition of CP content to the model can slightly improve the prediction (equation 4 and 5, Table 3). Moreover, statistical analysis

indicated that drN increase with OM digestibility without any significant difference between types of grass.

Protein digestible in the intestine

The value of PDIA obtained by INRA method varied largely from 15.2 to 36.5 g/kg DM and is greater than the measured value obtained by nitrogen flow with caulated sheep in rumen, duodenum and ileum which varied from 11.0 to 36.2 g/kg DM. The statistical analysis indicated that CP affect quadratically both predicted PDIA obtained by INRA calculation method and PDIA obtained by nitrogen flow method (equation 7 and 8, Table 3) with a tendency to have a significant difference between the two method for the intercept ($P=0.1$), but not on the slope ($P=0.46$). Otherwise, NDF content affect negatively PDIA value with no difference between the two methods either for the intercept ($P=0.3$) or for the slope ($P=0.25$). The tendency indicated that INRA method overestimates the PDIA value of tropical forages. The value of PDIN obtained by INRA method varied from 36.40 to 79.39 g/kg DM. However the PDIN obtained by measured nitrogen flow method varied from 29.04 to 65.03 g/kgDM. PDIN varied quadratically with CP content (equation 9, Table 3) without any significant difference between the two method for the intercept ($P=0.24$) and for the slope ($P=0.77$). NDF has no significant effect ($P=0.8$). The PDIE value obtained by INRA prediction varied from 68.01 to 89.08 g/kg DM. The corresponding value obtained by nitrogen flow method varied from 29.04 to 84.34 g/kg DM. The statistical analysis indicated that PDIE varied quadratically with CP content (equation 10 and 11, Table 3) with a tendency to have a significant difference between predicted and measured values for the intercept ($P=0.1$), but not for the slope ($P=0.30$). Moreover, NDF has no significant effect ($P= 0.63$). The PDIA, PDIN and PDIE were obtained via nitrogen duodenal and illeal flow. However, endogenous nitrogen was neglected. In the absence of measured data, we proposed prediction equations on the basis of CP and NDF content of the diet that are readily measurable and constituted the most limiting factors under tropical and warm conditions.

Table 3: Linear and multiple prediction equations for protein content of tropical forages obtained in this study and comparative equations obtained from previous study.

N° Eq	Global equation	n	R2	SD
1	All forages ED _N = 63.96 (± 7.42) - 0.04 (± 0.008) NDFg/kg DM + 0.11(± 0.058) CPg/kg DM - 0.00018 (± 0.021) CP ² g/kg DM	229	0.79	8.14
2	CPμ (g/kg DM) = 34.6 (± 17.12) + 0,062 (± 0.037) × FOM	39	0.92	7.00
3	CPμ (g/kg DM) = 45.2 + 0.0731 FOM (INRA, 2013)	707		7.60
4	drN (%) = 76.02 (± 5.75) - 0.25 (± 0.099) NDFg/kg DM	47	0.88	5.68
5	drN (%) = 70.72 (± 19) - 0.02(± 0.02) NDFg/kg DM + 0.06 (± 0.05)CPg/kg DM	47	0.9	5.70
6	drN = 31.48 (± 10.19) + 0.52 (± 0.17) Omd%	37	0.90	5.25
7	PDIA (g/kg DM) = - 36.51 (± 11.42) + 0.87 (±0.22)CPg/kg DM - 0.003 (0.001) CP ² g/kg DM (Nitrogen flow method)	13	0.68	6.00
8	PDIA (g/kg DM) = - 15.45 (± 11.42) + 0.87 (±0.22)CPg/kg DM - 0.003 (0.001) CP² g/kg DM (INRA calculaion method)	13	0.68	6.00
9	PDIN (g/kg DM) = - 7.44 (± 10.77) + 1.12 (± 0.21) CPg/kg DM - 0.004 (± 0.0009) CP ² g/kg DM (INRA calculation method and nitrogen flow method)	26	0.87	5.56
10	PDIE (g/kg DM) = 36.22 (± 15.01) + 1.03 (± 0.29) CPg/kg DM - 0.004 (± 0.0013) CP ² g/kg DM (Nitrogen flow mehod)	13	0.85	7.93
11	PDIE (g/kg DM) = -5.48 (± 15.01) + 1.03 (± 0.29) CPg/kg DM - 0.004 (± 0.0013) CP² g/kgDM (INRA calculation method)	13	0.85	7.93

n= number of observations; ED_N: effective degradability of nitrogen; CPμ: microbial crude protein; MOF: Fermented Organic matter in the rumen; drN: true digestibility of dietary protein in the small intestine; PIA: dietary protein in the intestine; Omd: organic matter digestibility.

Discussion

Fill unit

In this study, we choose to use chemical composition as a driving force to define the fill value of tropical forages for several reasons. The first one is to consider that the Omd can differ between the animal species for a same chemical composition of the forage. Moreover, chemical composition of forage is easier to determine than its Omd value. The second one, because in our study there is no enough comparative data of the VDMI between species for the same forage. The choice of our standard grass to build the fill units of tropical forage is based on the analysis of the database already established by INRA Guadeloupe from young forages (between 14 and 21 days) distributed ad libitum to Black Belly rams. The reference tropical forage which corresponding to one fill unit defined in our study contains 14.0% CP, 73.1% NDF and 39.3% ADF. Its Omd was equal to 60.0, 65.9 and 60.9% for sheep, goats and cattle, respectively. The corresponding values obtained for temperate forage in INRA system was 15% CP, 25% Crude fiber, 77% Omd, 75g/kg LW^{0.75} of DMI for sheep, (INRA, 1978).

Under tropical conditions in Cuba and Guadeloupe Xandé et al (1985) indicated that a 28-35 days regrowth grass with OMD higher than 58% consumed by the standard sheep presented an ingestibility equal to 68 to 71 g/kg LW^{0.75}. However, INRA (1989) indicated a value of 60 to 65 g/kg LW^{0.75}. These values are not too far from our proposal.

Compared with temperate forage, intake of our tropical reference grass is similar to the one reported by Dulphy et al (1989) for cattle. The evaluation of intake (61.34 g/kg LW^{0.75}) of the reference grass for meat goat seems low taking into account data of the literature reporting similar intake for meat goat comparing with sheep consuming good quality roughage (Alam et al., 1985). Moreover, a 1.07% higher intake was registered with goats consuming a low quality (Devendra, 2007).

It is known that the physiology of C4 grass (generally tropical grass) is different of this of C3 grass (generally temperate grass). The first one is characterized by a fast lignification rate with time (Wilson, 1991; Assoumaya et al., 2007). Moreover tropical forages are characterized by a high mastication and rumination time necessary to reduce the particle size and increase the rate of passage to the abomasum as indicated previously by Assoumaya et al. (2007). Indeed, they observed that mastication work to valorize 1kg of DM increased significantly for tropical forages compared to temperate ones for a similar chemical composition (15% depending of the level of CP and NDF). All the differences cited between temperate and tropical forages are low when low regrowth age is compared (Assoumaya et al. (2007). This difference of physiology between tropical and temperate grass underlight the low difference observed with the reference grass whereas high differences are reported for aging forage.

Energy content of tropical forages

Gross Energy (GE) content of tropical forages

The variation of GE content is within the ranges of variations observed previously for tropical forages (4138.75 to 4473 kcal/kg DM) by Kennedy et al. (2012) and temperate forages (4000 to 4600 kcal/kg DM) by Vermorel (1978). Moreover, by analyzing 139 tropical forages, Richard et al. (1990) indicated a value of 1.64 kcal/kg OM which is close to corresponding values indicated in table 2. From the coefficients of regression obtained for tropical forages in this study which not significantly different from those previously obtained for temperate or

tropical forages, it appears logic to adopt the same equations obtained from a large number of data.

Digestible energy (DE) content of tropical forages

The main factor of variation of the net energy content of forages is the digestibility of gross energy they contain and which is very closely related to the digestibility of organic matter (OMd). Previous works have already shown a strong correlation between the digestibility of energy and OMd whatsoever for temperate and tropical forages (Richard et al., 1990; Minson, 1990; INRA, 2007). Moreover, some other authors reviewed predictions from chemical composition by regressing DE against lignin, crude fiber or CP content (Schneider and Flatt, 1975). Average levels of digestible energy reported for tropical forages were lower than temperate forages which can be explained by differences in digestibility between these two categories of forage as indicated by Assoumaya et al. (2007). In fact, they indicated that OMd of tropical forages is about ½ point lower than temperate ones at the same level of NDF and CP. It appears that at the same level of OMd, lower energy digestibility is observed for tropical forages. For example, at the level of 80% OMd, INRA (1980) indicated that Ed% is equal to 80.65%. The respective values obtained in our study and by Richard et al. (1990) for tropical forages are 74.76 and 77.56%.

For every 1 unit increase in OMd%, Ed% is increased by about 0.94%. The same results were obtained for different categories of temperate forages (INRA, 2007) with an increase by about 0.97% of GE for every 1 unit increase in OMd%. The corresponding values for tropical forages of an increase by 0.98, 1% have been established by INRA (2007) and Richard et al. (1990). In spite of the small differences, it appears that it is necessary to predict specific equations of DE for tropical forages.

Metabolizable energy (ME) content of tropical forages

This study provided specific equations for tropical forages using measured data for ME through the urinary and gaseous (methane) energy losses obtained by respiratory chamber.

To compare our results with previous and actual ones, we adopted the expression of ECH4%GE, g/kgMOD and g/kgDM as indicated in others studies (Sauvant and Nozière, 2013; Yan et al., 2000; Kennedy and Charmley, 2012). GE lost as methane varies from 2.32

to 11.40 (mean = 6.19 ± 1.83) and CH₄ production varies from 8.33 to 35.7g/kg DM (mean = 19.41 ± 5.33). The same results have been established previously by Kennedy and Charmley (2012) for tropical forages and by Sauvant et al. (2011) for temperate forages.

Our result corroborated previous ones obtained for temperate forages concerning the negative effect of feeding level (FL) and curvilinear effect of MOD on methane production (Sauvant et al., 2011). Additionally our results are also similar to those of Pelchen and Peters (1998) using CPI, DEI and ME content in the same regression equation. But it appears in the two cases that tropical forages could produce more CH₄ than temperate ones at the same level of intake and MOD and DCPI, DEI and ME content. However in a recent study Eugène et al (2014), found higher but none significant CH₄ with C4 grasses versus C3 grasses.

Our results also corroborated the previous ones concerning the negative effect of fiber on CH₄ production or ECH₄% (Blaxter and Wainman, 1964; Moe and Tyrrell, 1979). This could be an indirect effect of DMI level via the rumen turnover rate. Some authors noted the eventuality of observing more energy loss in methane with tropical forages (Archimède et al, 2011; Pinares-Patino et al., 2003). The increase of ECH₄ with NDF content can be attributed to the negative and positive effect of fiber on passage rate and retention time, respectively (Assoumaya et al., 2007). According to Kennedy and Melligan (1978) and Okine et al. (1989) a 30% decline in methane production is observed when ruminal passage rate of liquid and solid phase increased by 54 to 68%. Another explanation can be summarized by the volatile fatty acid profiles including acetate to propionate ratio which is positively correlated with NDF and ECH₄ as demonstrated earlier (Nishida et al., 2007; Sauvant et al., 2011).

The mean value of energy lost in urine (3.96%GEI) is consistent with those established by Jentsch et al (1976) in sheep (4.8%) and bulls (3.3%), but slightly lower than the mean value (5%) indicated by INRA (1980). Our results entirely confirm those obtained by Sauvant and Nozière. (2013). Thus, there is no difference between UE losses for a same level of crude protein observed for tropical and temperate forages. For each one unit increase in CP%, energy lost in urine is increased by 0.017%. The value of 0.019% has been recently reported (Sauvant and Nozière, 2013). The increase of UE with CP content can be attributed to the positive effect of CP on urea nitrogen excretion for which UE depends largely. Khon et al. (2005) reported that there was a strong linear relationship between blood urea nitrogen (BUN) and UN excretion (UNE). Increasing the protein concentration of the diet leads to an increase in blood urea and that a part of urea is excreted via urine (INRA, 1980). Our observation confirm those obtained in cattle fed pasture by Klover and Aspin (2006) who indicated that

increased CP was associated with increased energy loss in urine (from 5-8% of GE) via urea that constitute 70-90% of UN. Urea energy (10.5 KJ/g) accounts for only 30-45% of UE (Bristow et al., 1992).

Really, the mean ratio between ME and DE (ME/DE=0.82) in our data base is similar to the mean value of: 0.81 reported by MAFF (1990) and AFRC (1993). The range of variation obtained from our database for tropical roughage is from 0.69 to 0.92 against 0.81 to 0.86 and 0.82 to 0.93 for AFRC (1993) and Vermorel and Bickel (1980) respectively. The importance of the range of variation of EM / ED with tropical forages advocates the use of a variable coefficient rather than a fixed coefficient as in most Feed System built for temperate feed. This raises the interest of prediction equations proposed for metabolizable energy.

In this study we have not made specific developments in net energy. The coefficient of conversion of DE to ME indicated that we can use the same coefficient obtained for temperate resources in INRA system.

Prediction Intestinal protein value of tropical forages

The estimation of PDI of any forages or concentrate necessitate obligatory the knowledge of effective degradability of nitrogen (ED_N), true digestibility of dietary protein in the intestine (drN) and microbial nitrogen (N_μ). The determination of ED_N has been well studied before by using in sacco degradability method. Compared to previous studies in which a fixed value of K_p was used to calculate ED_N such as the value of 6% fixed by INRA system (INRA, 1989), we hypothesis that K_p can varied with level of intake, level of fiber in the diet, rate of digestion, protein supplement and consequently with the chemical composition of the diet (NRC, 2001). For this reason, K_p was indexed on the chemical composition of the diet. For temperate forage, INRA (1988) proposed fixed values for each forage category (green forage, hay, silage with or without conservative, wilted silage). In the new INRA system (Sauvant and Nozière, 2013) proposed tabulated values of ED_N which are indexed on the NI level of the forage. For tropical forages, ED_N was fixed (53% to 63%) were used (Aumont et al., 1994b; Chapman and Norton, 1982; Parra et al., 1984; Cerneau et al., 1992; Xandé et al., 1989). The analysis of our database indicates an intermediate value of 57.4%. In fact these differences illustrate large variation of ED_N depending of the roughage related to their chemical composition. Consequently, we suggest direct measurement of ED_N or secondary, in absence of these values, prediction based on their CP and NDF content. In this study, the

prediction equation reflects the fact that the ED_N of forage increases curvilinearly with their CP content and decreased linearly with their NDF content with relatively high correlation coefficients. As the results obtained for temperate forage, the analysis of the database shows that changes in degradability and CP content are of the same magnitude. Thus, the ED_N increases of 5 points for an increase in CP from 10 to 15 %DM. The same tendency was obtained previously (Yan et al., 2004).

Data of mobile bags placed in the intestine used to measure drN are scanty under tropical conditions. In the INRA system (2007), values were proposed by type of temperate forages: green forage (0.75), hay (0.75), silage (0.6 to 0.7) and 0.7 for straw. In the tables of feed values of tropical forages, the INRA opted for a fixed value of 0.7. The determination of drN in our study was based on nitrogen flow (duodena and ileal). However we have neglected endogenous nitrogen. Analysis of our data for direct measurements of N intestinal digestion shows a high variability (0.5 to 0.85) around a mean value of 0.67. In the absence of data on nitrogen flow or in sacco degradability, drN can be predicted by the digestibility of OM or NDF content. In some cases this high variation of drN can be attributed to tannins since the tannin-protein bonds can partly hydrolyzed in the intestine (Aufrère and Guérin, 1996). Intestinal digestibility of ruminally undegraded feed CP varies considerably, depending on the feed type (Vanhatalo, 1995). The lower digestibility obtained in our study can be attributed to the high fiber and lower CP content of tropical forages, respectively as indicated by Nozière et al.(2005) who indicated a positive correlation between drN and CP content. However, the ranking of forages is likely to be affected by non-feed N. As digestibility of undegraded CP is affected by both the extent of ruminal degradation and feed type, measured values rather than a constant factor should be preferred in modern protein evaluation systems (Vanhatalo, 1995).

The microbial nitrogen flow (N_{μ}) is a key element in all rationing systems. In previous and actual systems, N_{μ} is predicted proportionally to organic matter apparently digested in the rumen or to organic matter fermented in the rumen (MOF) as used in INRA French system (Sauvant and Nozière,2013). The mean value obtained in our study for tropical forages (22.99 N_{μ} /FOM and 26.59 gN_{μ} /MOD) is comparable to the value of 23.2 gN_{μ} /FOM, 24 gN_{μ} /FOM and 26.3 $g N_{\mu}$ /kg MOD observed by several authors (INRA, 1989; Tamminga et al., 1994; Gosselink et al.,2003). However, it is lower than the mean value obtained for fresh forages (32.96) and dried forages (28.32) as illustrated by Minson (1990). The variation of N_{μ} can be attributed to more than one factor such as rumen environment, degree of carbohydrate degradation, dry matter intake, retention time and forage quality (Pathak, 2008). Compared to

the recent prediction linking CP μ to FOM established by Sauvants and Nozière (2013), it appears that for the same level of measured FOM, low production of measured microbial CP was obtained for tropical forages compared to temperate ones. Indeed, in our study for each one unit increase in FOM, CP μ is increased by 0.062 compared to an increase of 0.073 g (Sauvants and Nozière, 2013). Probably adaptations (including recycling of nitrogen in the rumen) may explain this result. NDF had a decreasing effect on efficiency of microbial synthesis, because a high concentration of NDF in dry matter is positively correlated with a low digestibility of forages and low concentrations of non structural carbohydrate and protein in dry matter. The decrease of the efficiency of microbial protein synthesis with NDF content can be attributed to negative effect on rate of ruminal degradation of protein which diminished the availability of N for microbes in the rumen and also to its effect on the rate of passage rate which is positively correlated to the efficiency of microbial protein synthesis.

The PDIA, PDIN and PDIE values of tropical forages obtained in this study varied largely for the two methods (INRA prediction vs measured method). This variation can be attributed to age of regrowth which affect CP content, to animal status, and to nitrogen fertilization used in each experiment as indicated previously by Aumont et al. (1995). The variation of PDIA, PDIN and PDIE is within the range of variation obtained for tropical or temperate forages (INRA, 1980). It appears that, in spite of their lower CP content, PDIA value of tropical forages can exceed 30g/kg DM.

Conclusion

The different equations established in this study showed that is possible, in some cases to adopt certain equations established by INRA system obtained from a larger number of data to characterize tropical forages. For energy value, we can adopt the relationship between CP and GE obtained by INRA system for tropical forages. But, for DE, it is necessary to establish specific equations for tropical forages since there is a difference on OMD between tropical and temperate forages. For Metabolizable energy, we can adopt the same coefficient of conversion of DE to ME used by INRA system. For protein value, it appears that is necessary to establish specific equations for tropical forages since there is a difference between true intestinal digestibility of dietary protein and between the efficiency of microbial synthesis of nitrogen. It appears that INRA prediction overestimates the PDI value of tropical forages in spite the same tendency obtained depending on the chemical composition.

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CHAPITRE 3
DISCUSSIONS GENERALES

1. Rappels des objectifs généraux du projet

L'objectif général de ce projet était de synthétiser des informations disponibles pour mieux conduire l'alimentation des caprins, ovins et bovins dans les régions chaudes. Pour atteindre cet objectif, il a été indispensable d'étudier en parallèle, les caractéristiques de l'animal et de l'aliment, qui sont à la base des systèmes d'alimentation. Ce projet s'est nourri du chantier SYSTALI de l'INRA (Sauvant et Nozière, 2013) portant sur la réactualisation du système d'alimentation INRA dont la dernière version date de 1989. Parallèlement à cette démarche, l'INRA a aussi ouvert un chantier sur la pratique de l'agro-écologie en élevage (Dumont et al, 2013) qui devrait impacter la conception des systèmes d'unité d'alimentation.

Le volet Aliment de ce projet a été conduit au moyen de méta-analyses alors que pour le volet Animal, des méta-analyses ont été associées à de nouvelles expérimentations (figure 2 : Introduction générale). Les objectifs étaient : 1) de quantifier les besoins énergétiques et protéiques d'entretien et de croissance de caprins, d'ovins et de bovins viande ; 2) de quantifier certaines réponses animales à l'alimentation ; 3) de quantifier les apports nutritionnels des fourrages.

2. Difficultés rencontrées lors de la réalisation du projet de thèse

2.1. Rareté relative de l'information sur l'utilisation digestive et métabolique des fourrages des régions chaudes

La constitution et l'analyse de bases de données ont représenté une part importante du projet de thèse. Nous avons construit 6 bases de données pour réaliser différentes estimations : 1) besoins des animaux et réponses animales aux rations ; 2) encombrement des fourrages ; 3) bilan énergétique de la digestion des fourrages ; 4) cinétique de dégradation ruminale de l'azote des fourrages ; 5) flux duodénaux d'azote alimentaire ; 6) flux duodénaux d'azote microbien. Bien que nombreuses, les données disponibles sur les fourrages n'étaient pas toujours suffisamment analytiques pour permettre d'affiner les systèmes d'alimentation en quantifiant avec précision l'utilisation digestive et métabolique des fourrages. Nous ne disposons pas de données (mesures en chambre calorimétrique) afin de quantifier l'efficacité de l'utilisation des nutriments pour la production (viande, lait) en milieu chaud avec des géotypes d'animaux des régions chaudes. Les fourrages des régions chaudes et les résidus de récolte sont connus pour être plus pauvres en sucres et plus riches en fibre que ceux des régions tempérées. Théoriquement, ils devraient conduire à des rapports Propionate/Acétate

plus faibles que ceux des fourrages tempérés. En conséquence, le rendement de l'utilisation métabolique des nutriments absorbés pourrait être différent des observations faites avec les fourrages tempérés. En ce qui concerne les protéines, les bases de données sur les flux duodénaux sont de petite taille et peu diversifiées en terme d'origine, ce qui les rend tributaires à un éventuel effet laboratoire. Ainsi, nous ne disposons pas de données de référence sur la digestion intestinale des protéines alimentaires (flux duodéal – flux iléal ; techniques des sachets mobiles). Le lien étroit entre les protéines et les parois végétales des fourrages relativement moins digestibles en régions chaudes, devrait entraîner de plus faibles digestibilités intestinales que celles mesurées avec les fourrages tempérés. Les ponts entre ces différentes bases sont par ailleurs faibles. Pour les données de croissance, nous ne disposons pas toujours d'information sur la composition du croît, connue pour être un important facteur de variation des besoins tant énergétiques que protéiques.

2.2. Des effectifs d'animaux et des formulations de rations sub-optimales

Au cours de l'expérimentation mise en place, nous avons été confrontés à deux contraintes majeures : 1) la formulation des rations ad hoc; 2) les effectifs d'animaux et leurs adaptations aux rations. Pour ce qui relève des rations, nous avons fait le choix de travailler avec des concentrés de l'agro-industrie et de valoriser de la farine de banane pour avoir des rations riches en énergie et carencées en protéines. Des contraintes techniques liées aux caractéristiques des presses à granulés du fabricant d'aliments prestataire ne nous ont pas permis de disposer de formules contenant plus de 60 % de banane. Nous avons donc utilisé une presse artisanale qui permettait de mélanger 90 % de farine de banane à 10 % de foin. Cependant, les contraintes techniques de cette presse artisanale ne nous ont pas permis d'incorporer la mélasse souhaitée, qui aurait conduit à une meilleure tenue du granulé et surtout à augmenter sa palatabilité. D'une façon générale, les granulés riches en farine de banane ont été faiblement consommés et nous avons constaté une relative surconsommation de foin dans ces rations. Cela ne nous a pas permis de discriminer les rations autant que nous l'aurions souhaité. Ces écarts entre les rations théoriques et les rations observées nous ont conduits à réaffecter les lots à six animaux sans que cela n'affecte les équilibres entre lots.

L'expérimentation était par ailleurs prévue sur 3 cohortes de 48 animaux, pour moitié des chevreaux Créole et pour l'autre moitié des agneaux Black Belly. Ce plan expérimental nous permettait de disposer de 6 animaux (caprins ou ovins) par traitement. Nous avons dû

supprimer une cohorte d'animaux, car ils étaient très parasités (strongles gastro-intestinaux) au moment du sevrage et nos traitements classiques se sont avérés inefficaces pour éliminer les strongles. La planification de la reproduction à l'unité expérimentale et la durée du projet de thèse n'ont pas permis de remplacer la cohorte manquante. Dans nos conditions de travail, il était aussi impossible d'augmenter le nombre d'animaux suivis en instantané du fait du nombre limité de loges individuelles et surtout de la lourdeur des mesures quotidiennes. En conséquence, nous avons travaillé avec quatre animaux par traitement, ce qui est relativement faible.

3. Leçons issues du projet de thèse

3.1. Les besoins nutritionnels des génotypes tropicaux plus élevés que ceux des génotypes tempérés

Les besoins énergétiques d'entretien des ruminants des régions chaudes sont plus élevés que ceux des ruminants des régions tempérées (Figure 1). En effet, les besoins d'entretien en EM obtenus dans notre étude (542.46 et 631.24 KJ/kg PM pour les petits ruminants et les bovins, respectivement) sont supérieurs à ceux des génotypes tropicaux obtenus par méta-analyse (Paul et al, 2003 ; Mandal et al, 2005 ; Paul et al, 2004) et les génotypes tempérés obtenus par des essais d'alimentation (INRA, 1989, 1988 ; NRC, 1989, 2000, AFRC, 1993, 1998 ; ARC, 1989, 1965). Du fait de la méthode de calcul utilisée, la régression linéaire, le besoin d'entretien est par différence ce qui n'est pas mobilisé dans la croissance. Plusieurs facteurs pourraient expliquer l'augmentation des besoins d'entretien. En milieu chaud, il y aurait une augmentation de l'énergie nécessaire pour dissiper la chaleur (CSIRO, 2007) bien que les génotypes locaux aient développé des stratégies d'adaptation (morphologie, glandes...). L'ingestion de rations généralement plus fibreuses en régions chaudes augmenterait le travail, donc un besoin d'énergie lié à la mastication (Goetsh et al., 1997). Il y a aussi un coût nutritionnel lié à l'environnement sanitaire souvent caractérisé par une occurrence forte de certains pathogènes (parasites notamment).

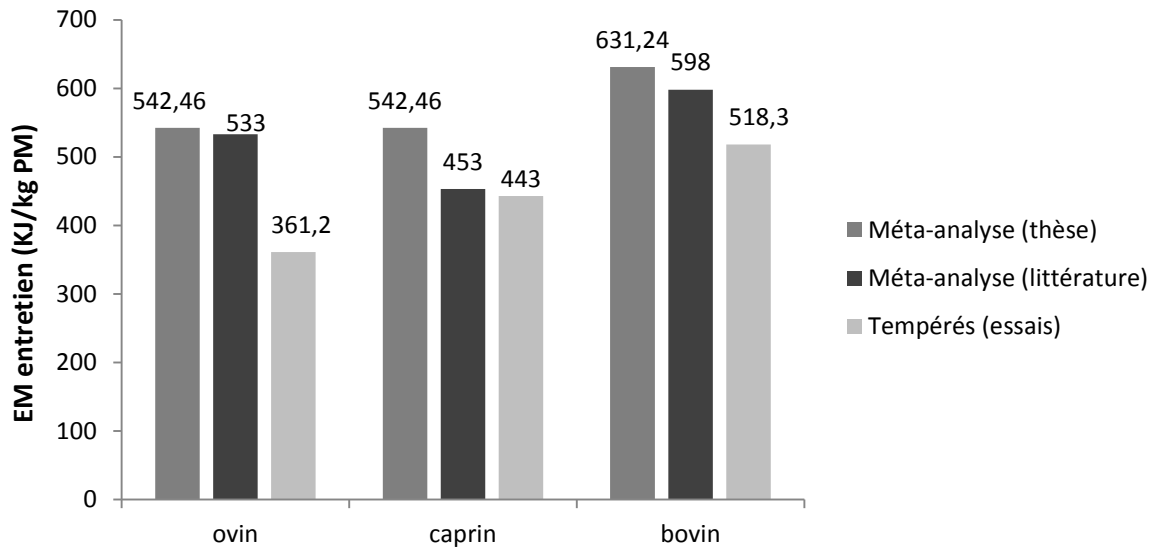


Figure 1 : Histogramme comparatif des besoins énergétiques d'entretien des ovins, caprins et bovins

Les estimations des besoins énergétiques pour la production (24.3 KJ/kg PM) sont de même ordre de grandeur et se situent dans les plages de variations que ceux estimés pour les génotypes tempérés ou tropicaux (NRC, 1989, 2000 ; ARC, 1989 ; AFRC, 1998 ; Sahlou et al, 2004 ; INRA, 1989 ; Paul et al, 2003 ; Mandal et al, 2005 ; Paul et al, 2004) (Figure 2). En effet, les génotypes tropicaux qui n'ont pas été sélectionnés pour la production de viande ont généralement une composition de croît plus grasse que celle des génotypes tempérés (Early et al., 2001). Le dépôt d'un gramme de protéines s'accompagne de 3 à 4 g d'eau alors que le dépôt de gras n'en contient pas. Ainsi, si une quantité donnée d'énergie métabolisable était transformée exclusivement en protéines, le GMQ induit serait 5 à 6 fois plus élevé que celui observé si cette même quantité d'énergie était convertie exclusivement en gras.

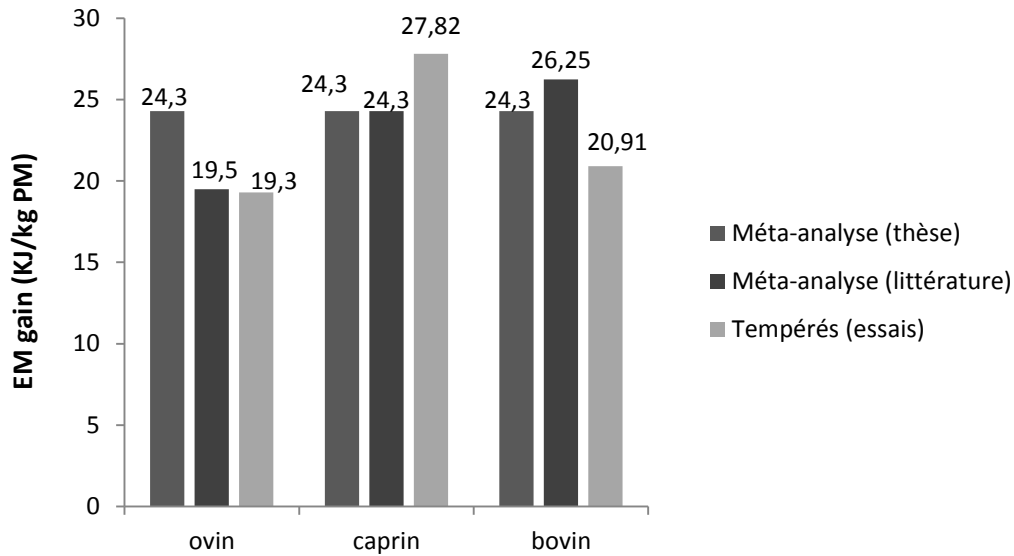


Figure 2: Histogramme comparatif des besoins énergétiques de croissance des ovins, caprins et bovins

En ce qui concerne les protéines, nous avons étudié les besoins et les réponses animales à l'apport de protéines. Cette approche est « grossière », car la nature des protéines (profil des acides aminés) impacte le rendement d'utilisation de ces dernières. Une part de la variabilité observée dans les réponses à l'apport de protéines est probablement liée à leur composition. Le rendement d'utilisation des protéines est d'autant plus important que son profil en acides aminés est proche de celui de la protéine à synthétiser. Les acides aminés sont utilisés pour la synthèse de protéines qui sont les constituants majeurs des muscles, tractus digestif et autres tissus. Au-delà, les protéines sont impliquées dans la synthèse de nombreuses enzymes et hormones impliquées dans différentes réactions métaboliques. Les acides aminés sont aussi des composantes des anticorps impliqués dans le système immunitaire. L'excès d'acides aminés relativement aux besoins de synthèses est désaminé puis oxydé, et peut contribuer à la néoglucogenèse.

Nos estimations indiquent des besoins protéiques d'entretien (3.53 g CPD/kg PM) sont plus élevés comparativement aux génotypes tempérés (NRC, 1985 ; INRA, 1989 ; Swidish system, 1995 ; Preston, 1966) (Figure 3). Pour les besoins de croissance, nos estimations (0.3g MAD/kg PM) sont plus élevées que ceux obtenus pour les génotyps tempérés (NRC, 1981, 1989 ; INRA, 1989 ; Fernandez et al, 2007 ; Irish system, 1980 ; Welkerson et al, 1993) (Figure 4) Comme indiquées pour les besoins énergétiques d'entretien, les estimations pour les protéines contiennent aussi probablement des besoins liés à des fonctions non-productives telles que l'adaptation à différents stress inhérents aux milieux chauds. Chez les animaux qui

ont été soumis à une sélection naturelle, il y a un déterminisme génétique de la partition de nutriments, entre les fonctions de production, de réserve, les fonctions de reproduction et les fonctions immunes (Friggens and Newbold, 2007). Par ailleurs, l'orientation des nutriments vers les cellules impliquées dans la fonction immunitaire devient prioritaire lors d'un épisode pathologique (Klasing and Iseri, 2013).

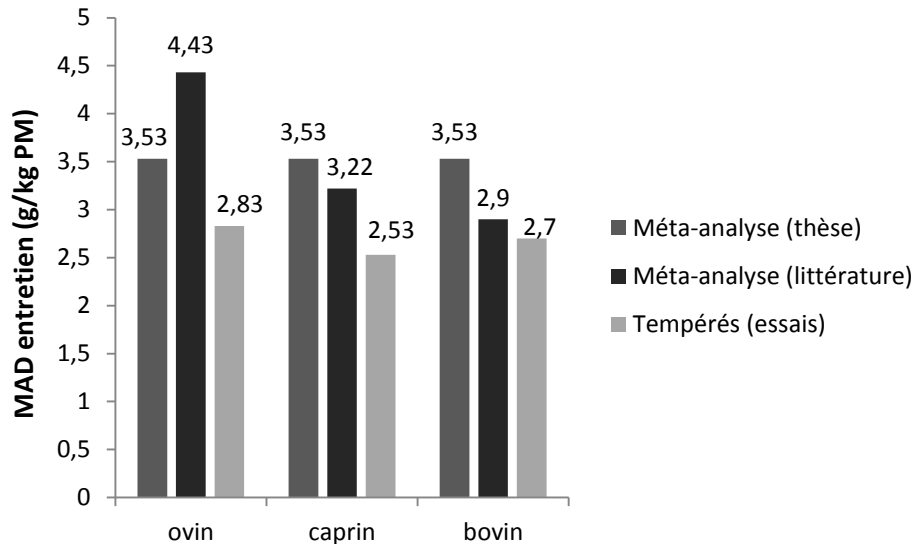


Figure 3: Histogramme comparatif des besoins protéiques d'entretien des ovins, caprins et bovins

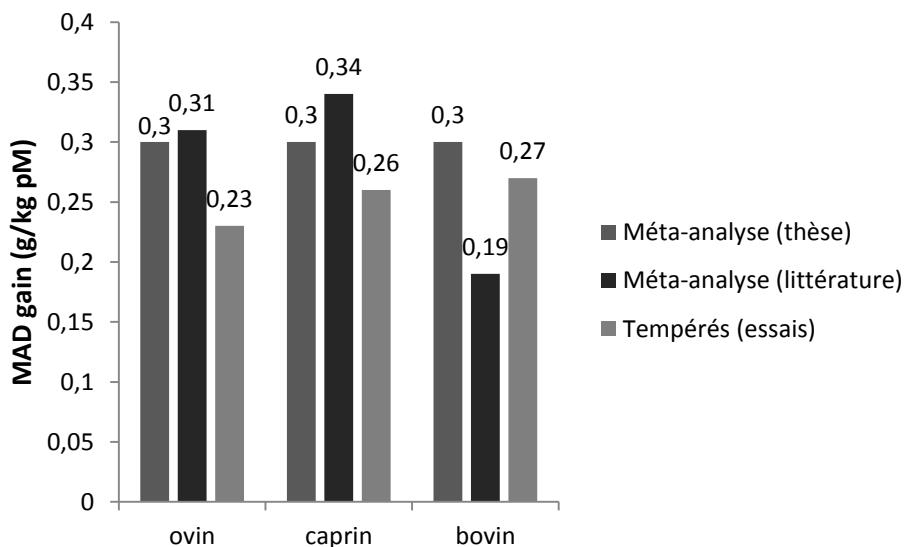


Figure 4: Histogramme comparatif des besoins protéiques de croissance des ovins, caprins et bovins

3.2. La hiérarchie des besoins entre espèces varie avec leurs modalités d'expressions

Le concept de poids métabolique est généralement utilisé pour comparer les espèces animales. Ce concept remonte aux travaux de Kleiber en chambre métabolique dans les années 30, qui conclut que le poids vif (PV) à la puissance 2/3 est la pondération la plus adéquate pour prédire le poids métabolique (PM) et pour comparer les besoins nutritionnels entre les espèces animales de tailles différentes (Kleiber, 1943). Cette valeur a cependant été critiquée à maintes reprises. Poppi et al (1981) a proposé la valeur de 0.86 pour comparer les ovins et les bovins. Cette valeur est proche de la valeur 0.86 issue de nos bases de données dans lesquelles étaient comparés les caprins, les ovins et les bovins. Ce coefficient étant proche de 1, nous avons fait le choix d'analyser nos données sur la base du $PV^{0.75}$ et du PV. Nos résultats indiquent que le choix du coefficient conditionne les conclusions dans les comparaisons inter espèces. Ainsi les besoins énergétiques des bovins relativement aux petits ruminants sont plus ou moins élevés suivant qu'ils soient exprimés en PV ou $PV^{0.75}$ alors que ces besoins étaient identiques quand ils étaient exprimés en $PV^{0.862}$.

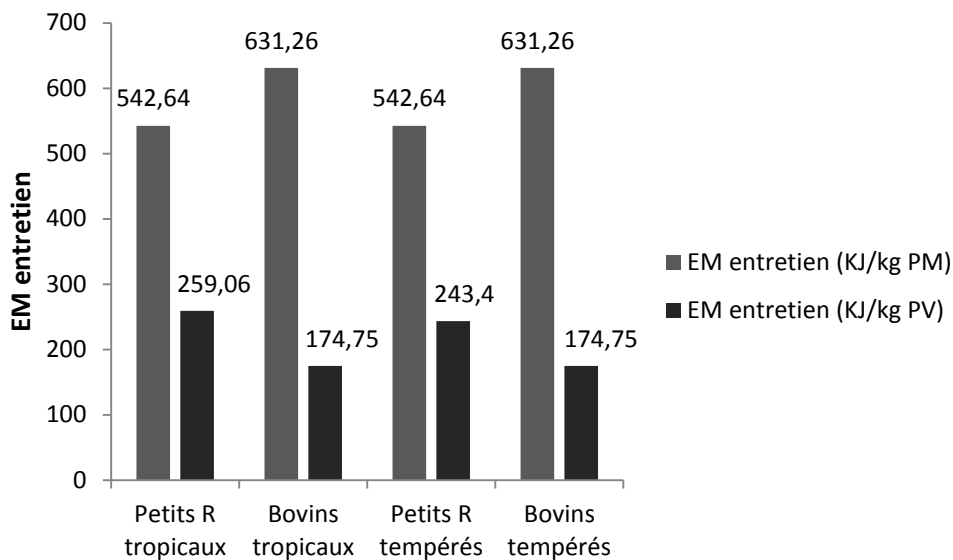


Figure 5: Histogramme comparatif des besoins énergétiques d'entretien par rapport à l'unité de poids entre les petits ruminants et les bovins

3.3. Le système d'unité d'alimentation énergétique et protéique d'INRA, basé sur une approche mécaniste de l'utilisation des aliments, conduit potentiellement à une bonne évaluation des ressources alimentaires

Le système d'unité d'alimentation énergétique et protéique de l'INRA, en cours de révision (Sauvant et Nozière, 2013) permettrait une bonne évaluation des ressources tropicales. Cependant certains coefficients doivent être révisés pour tenir compte de la composition spécifique des ressources fourragères disponibles en régions chaudes. Ainsi, l'évaluation de l'énergie métabolique souffre en partie de la faiblesse des bases de données comme en témoignent les conclusions des travaux d'Archimède et al (2011) et Eugène et al (2014). Le premier cité, en accord avec Kennedy et Charmley (2012), indique une production de méthane plus importante avec les fourrages en C4 versus les C3. Eugène et al (2014) a travaillé avec une base de données plus grande mais qui demeure modeste pour les ressources fourragères des régions chaudes et un modèle d'analyse statistique différent. Ils ne trouvent pas de différences significatives entre ces 2 types de ressources bien que les émissions de CH₄ étaient numériquement plus élevées avec les graminées en C4.

Il n'y a pas non plus de données en quantité suffisante qui permettent de déterminer d'éventuels coefficients spécifiques aux ressources fourragères des régions chaudes, pour passer de l'énergie métabolisable à l'énergie nette. Une approche théorique permet cependant de formuler l'hypothèse que ces coefficients sont probablement différents car les flux de nutriments énergétiques issus de rations très fibreuses et pauvres en glucides solubles sont plus pauvres en propionate et glucose.

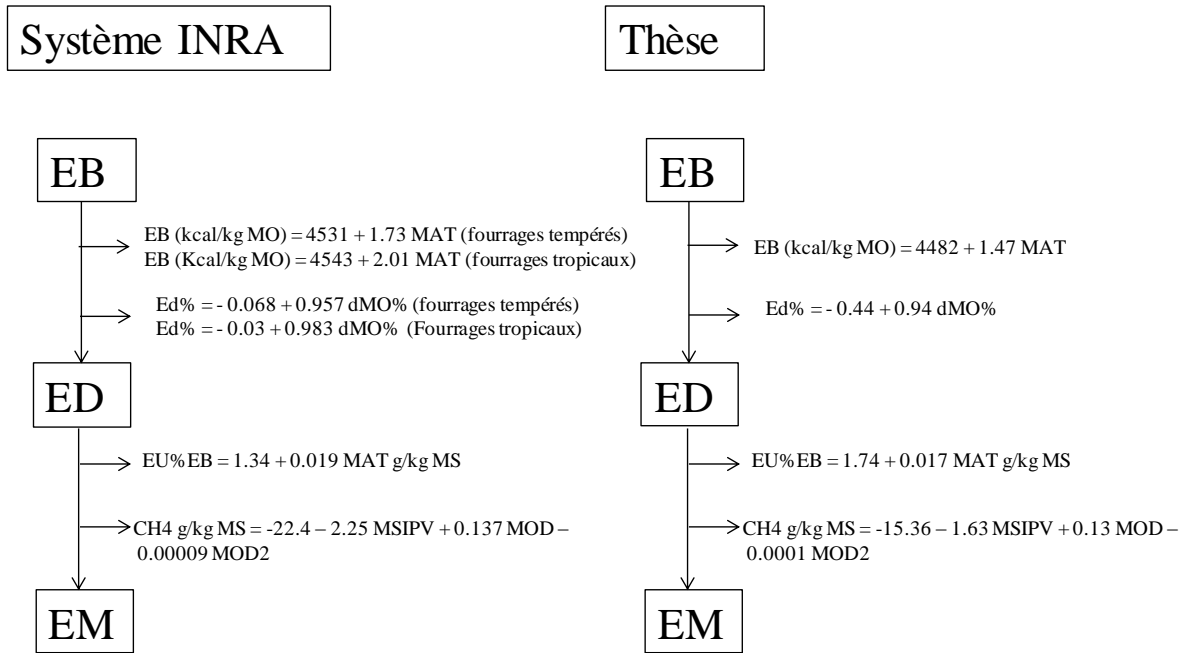


Figure 6 : Comparaison des résultats obtenus par le système INRA et les résultats obtenus par la présente étude.

3.4. Les réponses animales à l'alimentation et l'évaluation multicritères des ressources végétales répondent aux nouveaux challenges de l'élevage

Dans le cadre de ce projet, nous avons croisé l'approche de la détermination des besoins des animaux (article n°1) et de la réponse des animaux à l'alimentation (article n°2). La première approche est relativement classique même si relativement peu d'études ont été réalisées. Elle relève cependant principalement et historiquement d'une vision relativement « productiviste » de l'élevage. L'objectif intrinsèque de cette démarche est de quantifier les besoins afin d'apporter en quantité et qualité les nutriments nécessaires pour maximiser les performances. « L'amélioration » génétique des animaux d'élevage, bien que moins pratiquée dans les régions chaudes relativement aux régions tempérées, a considérablement augmenté le potentiel de production comparativement à celui qui leur était conféré par la simple sélection naturelle sous l'emprise de l'environnement. Il y avait un certain équilibre entre les fonctions productives et non-productives. En milieu chaud, parmi les fonctions non-productives on peut citer : l'adaptation à la chaleur, à certaines pathologies, la variabilité des disponibilités alimentaires. La maximisation du potentiel de ces ruminants, relativement performants dans le contexte tropical et chaud, peut nécessiter les recours à des rations relativement riches, imposant d'aller puiser sur des niches alimentaires (tubercules, fruits, céréales, pois...)

d'intérêt pour les monogastriques (dont l'homme). Cela peut entraîner une certaine concurrence sur les petits territoires, sur les grands territoires où la climatologie rend de grandes surfaces inaptées aux cultures. En conséquence, dans de nombreuses régions tropicales et chaudes, la question de l'élevage de ruminant est davantage une valorisation optimale des ressources disponibles, que la maximisation des performances de l'animal. Dans cette démarche, s'inscrivent bien celles des lois de réponses.

Au-delà de la recherche de valorisation de la biomasse disponible, de nouveaux défis s'imposent à l'élevage dont celui de réduire les impacts négatifs sur l'environnement. Des stratégies alimentaires optimales peuvent permettre d'y contribuer. Ainsi, nous avons quantifié la relation positive entre l'ingestion d'azote et son excrétion urinaire (article n°2). L'azote urinaire est une source potentielle de pollution s'il n'est pas géré au sein du système d'élevage et/ou du territoire. Nous avons aussi montré (article n°4) que l'émission de méthane augmentait avec la fibrosité des rations ce qui est une « limite » de la valorisation des rations fibreuses. Cela montre la limite de l'évaluation (ressources animales et végétales) monocritère et la plus-value d'évaluations multicritères basées sur l'optimisation de différentes fonctions productives et non productives.

3.5. Les réponses animales aux apports protéiques et énergétiques

Les contraintes majeures de l'élevage des ruminants dans les régions tropicales et chaudes résident dans les faibles disponibilités en quantité et en qualité, les limitations physiques de l'ingestion des fourrages et le déséquilibre entre les nutriments extraits des aliments et les nutriments nécessaires pour satisfaire les besoins des animaux surtout l'énergie et les protéines (Ibrahim et al, 1995). Les niveaux énergétiques et protéiques ont un effet significatif sur les performances de croissance et sont en accord avec les résultats de Khorshidi (1996) et Kioumaris et al (2008). L'augmentation de l'ingestion des protéines est accompagnée par une augmentation de la croissance des ovins, caprins et bovins quelque soit le niveau énergétique. En effet, à même niveau d'ingestion de protéine, l'augmentation de l'apport énergétique permet la production de plus d'énergie métabolisable pour les micro-organismes du rumen résultant en une augmentation de la synthèse des protéines microbiennes et la quantité de protéines disponibles pour l'animal (Early et al, 2001). Ce ci est la raison pour la quelle, à une ingestion nulle de protéine, le GMQ des ovins, caprins et bovins a augmenté de – 0.59 g/kg

PM à 2.29 g/kg PM quand le niveau énergétique est passé de moins de 1.2 l'entretien à plus de 1.2 l'entretien.

L'augmentation de l'ingestion de l'énergie métabolisable est accompagnée par une augmentation de la croissance quelque soit les niveaux protéiques. Cependant, à même ingestion d'énergie, la croissance est plus importante pour les niveaux protéiques les plus élevés. Ce ci est peut être du à une meilleure croissance microbienne et un changement de processus de fermentation dans le rumen résultant à une augmentation de la production d'AGV avec plus de propionate (Kabir et al, 2002). Ce ci entraîne une amélioration de l'équilibre énergétique et la rétention azotée et par conséquent une augmentation de la croissance quand le niveau protéique passe de 7 à + 15%.

3.6. Intérêt des modèles biologiques tropicaux

Nos résultats confirment l'intérêt d'utiliser des modèles végétaux et animaux des régions chaudes dans la production de connaissances. Ces ressources résultent de l'adaptation au milieu biophysique en absence de sélection sur des critères de productivité. Elles apportent de la variabilité dans les réponses animales ce qui donne plus de généralité à la connaissance produite. Au-delà, dans le contexte de l'agro-écologie, elles interpellent sur l'intérêt de la valorisation des fonctions productives et non-productives en élevage. La définition de stratégies pour orienter des flux de nutriments entre ces différentes fonctions pourrait constituer des pistes de recherche.

CONCLUSION ET PERSPECTIVES

Les principaux apports de ce travail de thèse sont :

- L'estimation des besoins énergétiques et protéiques des ruminants d'élevage en régions chaudes.
- La quantification de certaines réponses animales (ingestion, croissance, excrétion azotées) à l'alimentation en région chaude.
- La quantification de certains coefficients qui permettent une meilleure prédiction de la valeur alimentaire des fourrages en régions chaudes.

Plus largement ce projet est une contribution à la révision en cours du système d'alimentation de l'INRA pour le volet tropical.

Ce projet qui était fortement basé sur la valorisation des informations existantes via des méta-analyses, nous a donné l'opportunité de faire un état des connaissances produites et d'identifier certains chantiers qui permettront de progresser dans les domaines de l'évaluation multicritères des aliments et les réponses multiples des ruminants d'élevage à l'alimentation.

En ce qui concerne l'évaluation des ressources alimentaires (fourrages, céréales, racines, tubercules, fruits, protéagineux), comme pour les aliments tempérés il conviendrait de les caractériser à travers des flux de nutriments moins agrégés que ceux (protéines, énergie) qui sont proposés aujourd'hui. L'appréciation de ces flux de nutriments (acides gras volatils, acides gras, acides aminés) permettra de mieux prédire les réponses animales multiples dans le contexte de l'agro-écologie. Une première étape vers cette démarche serait de quantifier la digestion pré et post intestinale des protéines alimentaires, de l'amidon (céréales, racine, tubercules, fruits, protéagineux).

Les systèmes d'alimentation actuels même rénovés gagneront certes en précision pour prédire les performances de production mais resteront en décalage vis-à-vis des nouveaux défis induits par le développement de l'agro-écologie en élevage. L'une des conséquences de ce dernier est d'une part, l'évaluation multicritères des ressources végétales, d'autre part, la quantification des réponses à l'alimentation. Ces deux démarches sont liées.

L'évaluation multicritère des aliments doit progresser sur le concept, la définition d'indicateurs et sur les modalités de mesure.

Afin d'apprécier les réponses animales multiples, les dispositifs expérimentaux qui sont aujourd'hui principalement formatés pour des études monocritères doivent aussi évoluer pour permettre des approches globales des réponses animales (production, qualité des produits, impacts environnementaux, bien être et santé...) à l'alimentation.

De point de vue scientifique, les résultats obtenus dans cette thèse constituent une grande partie du projet SYSTALI conduit par l'INRA qui a comme objectif la rénovation des unités alimentaires des ruminants. Cependant, de point de vue pratique, ces résultats donnent aux éleveurs des nouveaux scénarios pour bien maîtriser leurs itinéraires de production via l'évaluation des performances animale, la quantité et la qualité des aliments à fournir et les besoins des animaux. Ils permettent aussi aux éleveurs d'évaluer l'impact de leurs pratiques alimentaires sur différents critères tels que le niveau de production, la pollution de l'environnement pour s'adapter à l'évolution des contraintes économiques, environnementales et sociétales qui agissent sur la durabilité des systèmes d'élevage qui ne cessent d'évoluer.

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