



Net productivity, a new metric to evaluate the contribution to food security of livestock systems: the case of specialised dairy farms

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Abstract

The increasing human population and demand for animal food products raise the issue of impacts of animal systems on food security caused by their use of human-edible feed and/or tillable land. The utility of replacing animal systems with potential food-crop systems needs to be assessed but is associated with many uncertainties. Some metrics analyse the contribution of current animal systems to food security, especially the dimension of food availability. These methods address feed conversion efficiency (i.e. total ('gross') or human-edible ('net')) or the efficiency of agricultural land use (i.e. total, permanent grassland, and tillable land) but never both simultaneously. The purpose of this study was to develop a new metric—'net productivity'—to represent the performances of current animal systems more accurately by considering both the use of human-edible feed and agricultural land. Through a protein assessment, we analysed the ability of the existing and the new metrics to assess the performances of 111 dairy farms in Wallonia (Belgium). We found that net productivity was positively correlated with both metrics of feed conversion efficiency and negatively correlated with the three metrics of land use. To analyse the influence of farm characteristics, we grouped the farms into four clusters using *k*-means clustering based on these metrics of contribution to food security and then performed redundancy analysis to select the most influential farm characteristics aiming to highlight contrasted farm strategies. The highest net productivity was reached by an 'intensive and net efficient' farm strategy, which had intensive grass-based management, high milk production per cow, appropriate use of concentrates, and well-managed dairy followers (i.e. replacement heifers and calves). The newly developed metric of net productivity can be useful to quantify the contribution of dairy systems to food security by considering both the use of human-edible protein and agricultural land simultaneously.

Keywords Feed/food competition · Land use · Food production · Human-edible protein · Multivariate analysis · Redundancy analysis

1 Introduction

The demand for animal food products is expected to rise as the world's human population continues to increase (UN 2019) and include more animal products in its diet (Alexandratos and Bruinsma 2012). Unfortunately, the associated expansion

of livestock farming threatens food security, especially the dimension of food availability (FAO 2015). Animal production includes a significant share of high-quality feed in animal diets (e.g. cereals), which results in competition between human food and animal feed (Wilkinson 2011). Worldwide, 14% of the animal feed consumed is considered human-edible (Mottet et al. 2017). According to the same authors, animal production also uses large amounts of land, which includes 1.3 billion hectares of permanent grasslands but also 1.2 billion hectares of tillable land from which 211 million hectares is dedicated to cereals. Although the efficiency of feed use by animals is increasing due to technical advancements, such as diet optimisation and genetic selection (VandeHaar et al. 2016), feed conversion will always have inherent metabolic losses according to Lindeman's (1942) 10% law of ecological efficiency. From a food-security perspective, it seems more efficient to use human-edible feed in human diets rather than

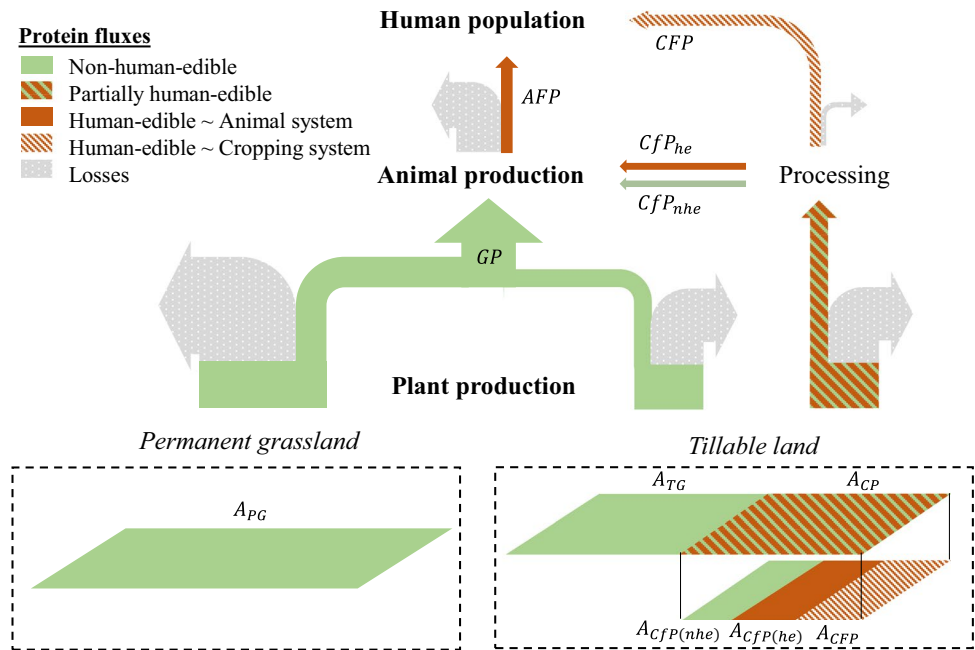
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Fig. 1 Protein fluxes in a mixed crop-livestock agroecosystem, with losses between trophic levels due to metabolic losses based on the 10% law of Lindeman (1942) and unused protein from, e.g. losses at feed harvest or storage; losses due to processing crops (unused protein only) were assumed to be lower than losses between trophic levels. Abbreviations are as follows: AFP: animal-food protein, CFP: crop-food protein, CfP_{he} : human-edible crop feed protein, CfP_{nhe} : non-human-edible crop feed protein, GP: grass-based protein, A_{CP} : crop protein area, A_{CFP} : CFP area, $A_{CfP(he)}$: human-edible crop feed protein area; $A_{CfP(nhe)}$: non-human-edible crop feed protein area, A_{TG} : temporary grassland area, A_{PG} : permanent grassland area.



in livestock diets (Fig. 1). Nevertheless, as animals can transform non-human-edible resources, such as industrial by-products and grass-based fodder, into rich and highly digestible food products, their place in agroecosystems can be adapted to improve food security (van Zanten et al. 2019).

Several metrics have been developed to quantify the contribution of animal systems to the food-availability dimension of food security (Fig. 2). They emphasise protein, as it is a key feature of animal food in human nutrition (Randolph et al. 2007). One metric is the ‘gross’ feed conversion efficiency,

which quantifies the amount of animal-food protein (AFP) produced per unit of protein consumed (Vandehaar 1998), but does not represent the amount of human-edible protein consumed. This is why ‘net’ efficiency was subsequently developed (Wilkinson 2011) to take into account only proteins that are edible for humans (CfP_{he} , Fig. 1). Nevertheless, farms with the highest net efficiency can still use large amounts of land (Ertl et al. 2015). As arable land and grassland are finite resources, the efficiency of land use by livestock is considered in a second set of metrics to assess their contribution to food

		Current animal system		Potential food-crop alternative
		Gross metrics	Net metrics	
Agricultural land efficiency	Feed conversion efficiency	Gross efficiency: $\frac{AFP}{GP + CfP_{nhe} + CfP_{he}}$	Net efficiency: $\frac{AFP}{CfP_{he}}$	
	Productivity	Gross productivity: $\frac{AFP}{A_{PG} + A_{TG} + A_{CfP(nhe)} + A_{CfP(he)}}$	Net productivity: $\frac{AFP - CfP_{he}}{A_{PG} + A_{TG} + A_{CfP(nhe)}}$	Land Use Ratio: $Pot. \left(\frac{PFC}{A_{PG} + A_{TG} + A_{CfP(nhe)} + A_{CfP(he)}} \right)$
	Land Use	Total land use: $\frac{A_{PG} + A_{TG} + A_{CfP(nhe)} + A_{CfP(he)}}{AFP}$	Perm. grassland use: $\frac{A_{PG}}{AFP}$ Tillable land use: $\frac{A_{TG} + A_{CfP(nhe)} + A_{CfP(he)}}{AFP}$	$\frac{AFP}{A_{PG} + A_{TG} + A_{CfP(nhe)} + A_{CfP(he)}}$

Fig. 2 Equations for calculating the metrics for contribution to food security grouped into (1) feed conversion efficiency or agricultural land efficiency (productivity and land use) and (2) metrics that represent the current animal system or compare it to a potential food-crop alternative. Metrics for the current animal system are further divided into gross (all feed) and net (human-edible feed) metrics. Abbrevia-

tions are as follows: AFP: animal-food protein, CFP: crop-food protein, CfP_{he} : human-edible crop feed protein, CfP_{nhe} : non-human-edible crop feed protein, GP: grass-based protein, A_{CP} : crop protein area, $A_{CfP(he)}$: human-edible crop feed protein area, $A_{CfP(nhe)}$: non-human-edible crop feed protein area, A_{TG} : temporary grassland area, A_{PG} : permanent grassland area.

security. One metric is to assess the AFP productivity (i.e. gross productivity) of the land used. Land use per unit of AFP (de Vries and de Boer 2010) is the inverse of gross productivity and can be separated into tillable land (i.e. crops (A_{CP}) and temporary grassland (A_{TG})) and non-tillable land (i.e. permanent grassland, A_{PG}) (Peters et al. 2014). This dichotomy partially integrates the concept of feed-food competition, as tillable land can produce more crop-food protein (CFP).

While these metrics represent performances of current livestock systems, the land use ratio (LUR) compares, for a given area, the protein production of a current livestock system to that of a potential food-crop system (van Zanten et al. 2016). Which food-crop-based rotation is used in the comparison influences the LUR strongly (Hennessy et al. 2021) and has high uncertainties in its long-term viability (e.g. fertility, pest management) and the variability in expected yields as a function of the biophysical context and farm management systems (Arata et al. 2020). For example, for Belgium, van Zanten et al. (2016) used a reference wheat yield of 8.405 t dry matter (DM) ha^{-1} , while wheat yields in its Walloon region can range from 5.5 to 9.5 t DM ha^{-1} depending on the province (de Wit et al. 2012).

Due to the uncertainty associated with considering replacing animal productions with food crops, the purpose of this study was to develop a new metric that considers the use of both human-edible protein and agricultural land to represent more consistently the contribution of current animal systems to the food availability dimension of food security. The metric is based on the ecological concept of 'net productivity', which represents the amount of energy transferred from a lower to a higher trophic level per unit of time and space (Urry et al. 2017), applied to animal food systems. Thus, the net productivity of an animal food system represents the net amount of AFP that animals (lower trophic level) provide to humans (higher trophic level) per unit of time and space. We used this metric to assess performances of specialised dairy farms in the Walloon region, whose high diversity of dairy systems (Hennart et al. 2010) allowed us to evaluate net productivity with a sample of farms characterised by a high diversity of characteristics. We tested the hypotheses that (1) net productivity was positively correlated with gross and net feed conversion efficiencies and negatively correlated with the efficiency of agricultural land use (i.e. total, permanent grassland, and tillable land) and (2) that it is maximised by dairy farm characteristics that differ from those identified by existing metrics.

2 Materials and methods

2.1 Sample description

Accounting data from 111 specialised dairy farms (milk production of 3529–9919 l cow^{-1} $year^{-1}$) were obtained from three agricultural advisory organisations in the Walloon region: the Department of Agricultural Economic Analysis (DAEA; $n = 51$), the Walloon Breeders Association (Elevéo; $n = 46$), and the Provincial Service for Information, Management, and Agricultural Vulgarisation (SPIGVA; $n = 14$). The sample contained six organic farms. The data from DAEA came from 2016 to 2018, while those from Elevéo and SPIGVA came from 2014 to 2016. These data were checked carefully and validated by the advisory organisations. The mobilisation of the data of those three organisms was aimed at covering a large diversity of dairy systems and a greater area of the Walloon region. From these data, we calculated metrics of contribution to food security and farm characteristics using the mean of the three available years to minimise the influence of interannual and stock variations.

2.2 Estimation of metrics of contribution to food security

We calculated six metrics to characterise the contribution of the dairy subsystem of each farm to food security: gross efficiency, net efficiency, total land use, permanent grassland use, tillable land use, and net productivity. We calculated net productivity as the AFP produced minus the human-edible protein consumed, per unit of 'non-human-edible area' and per year (Fig. 2). The non-human-edible area equals the area allocated based on the non-human-edible fraction of the protein produced on the land used. The human-edible area is subtracted to avoid penalising the use of human-edible protein twice (first as a quantity and then as an associated area of tillable land). Gross productivity was not considered, as it equals the inverse of total land use.

Net and land-use metrics were calculated by estimating annual production of human-digestible protein (HDP). To this end, we estimated crude protein (CP) production corrected with digestible indispensable amino acid scores (DIAAS) for feed and animal products to capture differences in protein quality (FAO 2013):

$$DIAAS(\%) = \frac{\text{mg of digestible in dispensable amino acid per g of dietary protein}}{\text{mg of the same amino acid per g of reference protein}} \times 100 \quad (1)$$

We used the DIAAS coefficients of a reference protein for a 6-month to 3-year-old child, as described by Ertl et al. (2016a). Gross efficiency was calculated using the CP content only, as it would be incorrect to sum the HDP of

human-edible feedstuff with the CP of non-human-edible feedstuff (e.g. grass). The following methodology describes how the coefficients were calculated based on the metrics' equations (Fig. 2).

2.2.1 Human-edible animal food sources

The amount of AFP was estimated from the amounts of milk sold and produced meat. We estimated the human-edible fraction of animals using their live weight per age and sex category (Table 1) and assumed a human-edible protein fraction

(hePF) of 45% and a CP content of 0.158 kg CP per kg live weight for the animal parts currently included in the human diet (i.e. meat, offal, and by-products) (Laisse et al. 2018). For milk, we multiplied the kilogram of milk sold (and not given to calves) by its CP content. Because the milk had been sold, we assumed that all of it was human-edible (Eq. 2).

$$\begin{aligned} \text{AFP}(\text{kg HDP year}^{-1}) = & \sum_{\text{categories}} (\text{animals sold}_{\text{category}}(\text{year}^{-1}) \times \text{live weight}_{\text{category}}(\text{kg}) \times \text{hePF}(\%)/100 \\ & \times \text{CP}_{\text{meat}}(\text{kg CP kg live weight}^{-1}) \times \text{DIAAS}_{\text{meat}}(\%)/100) + \text{milk sold}(\text{kg year}^{-1}) \\ & \times \text{CP}_{\text{milk}}(\text{kg CP kg milk}^{-1}) \times \text{DIAAS}_{\text{milk}}(\%)/100 \end{aligned} \quad (2)$$

For gross efficiency, the AFP was calculated without DIAAS correction and expressed as CP.

2.2.2 Total consumption of feedstuff

The quantities of intra-consumed (IC) crops and purchased concentrates, as well as their CP contents, were included in the accounting data. We estimated the quantity of on-farm IC fodder based on farm area (FA), which was distinguished in the data into the area of permanent grasslands (FA_{PG}), temporary grasslands (FA_{TG}), and silage maize (FA_{maize}). We considered two types of fodder: grass-based fodder (permanent and temporary

grasslands) and maize silage. We based our estimates of the quantities IC on regional yields (Table 2) corrected by the dry matter intake (DMI) capacity of the herd, as explained in the following step. DMI varied by sex and age category (Table 1). DMI of dairy cows (DC) was calculated as in Roseler et al. (1997):

$$\begin{aligned} \text{DMI}_{\text{DC}}(\text{kg DM cow}^{-1} \text{ day}^{-1}) = & -0.293 + 0.0968 \times \text{LW}^{0.75}(\text{kg}) \\ & + 0.372 \times \frac{\text{FPCM}(\text{kg cow}^{-1} \text{ year}^{-1})}{365(\text{day year}^{-1})} \end{aligned} \quad (3)$$

where FPCM is the fat-and-protein-corrected milk production (CVB 2016):

$$\begin{aligned} \text{FPCM}(\text{kg cow}^{-1} \text{ year}^{-1}) = & (0.337 + 0.116 \times \text{milk fat}(\%) + 0.06 \times \text{milk protein}(\%)) \\ & \times \text{milk yield}(\text{kg cow}^{-1} \text{ year}^{-1}) \end{aligned} \quad (4)$$

Per category of animal, DMI was multiplied by the corresponding mean number of animals per year (average annual

presence) and summed across the categories to obtain the total annual DMI of the herd:

$$\begin{aligned} \text{herd DMI}(\text{kg DM year}^{-1}) = & \sum_{\text{categories}} (365 \times \text{DMI}_{\text{category}}(\text{kg DM day}^{-1}) \\ & \times \text{average annual presence}_{\text{category}}(\text{year}^{-1})) \end{aligned} \quad (5)$$

Table 1 Live weight and dry matter intake (DMI) by sex (M male, F female) and age category used to describe the animals. Live weights were estimated from regional growth curves for the Holstein breed.

DMI came from a regional project for followers (i.e. replacement heifers and calves) and from Roseler et al. (1997) for dairy cows (DC).

Sex and age (months) categories	0–2M	2–6M	6–12M	12–24M	> 24M	0–6F	6–12F	12–24F	>24F	DC
Live weight (kg)	70	125	272	380	520	125	272	380	520	650
DMI (kg DM day ⁻¹)	0	3	5	8	9	3.7	6.7	8.6	9.8	(Eq. 3)

Table 2 Mean, standard error (se), and the sample size (*n*) for crude protein (CP) content and dry-matter (DM) yield of grass-based fodder and maize silage from unpublished data from Walloon organisations: ¹REQUASUD (Walloon network of accredited analysis laborato-

ries), licence A04/2021, 2014-2019; ²CRA-W (Walloon Agricultural Research Centre), grass growth observatory, 2014-2016; ³CIPF (Independent Fodder Promotion Centre), maize yield observatory, 2014-2016.

	CP content (kg CP kg DM ⁻¹) Mean (se)- <i>n</i>	Yield (kg DM ha ⁻¹ year ⁻¹) Mean (se)- <i>n</i>
Grass-based fodder	0.15 (0.037)-345 ¹	8000 (1800)-40 ²
Maize silage	0.076 (0.0088)-165 ¹	18000 (1300)-294 ³

We determined the quantity of IC fodder by subtracting the IC crops and purchased feed from the herd DMI:

$$\text{IC fodder (kg DM year}^{-1}\text{)} = \text{herd DMI (kg DM year}^{-1}\text{)} - (\text{IC crops (kg DM)} + \text{purchased feed (kg DM)}) \tag{6}$$

We then calculated a fodder yield correction (Eq. 7) to adjust IC grass and IC maize silage individually to

DMI based on their theoretical yields (Table 2) (Eq. 8 and 9):

$$\text{fodder yield correction (\%)} = \frac{\text{IC fodder (kg DM year}^{-1}\text{)}}{\sum_{\text{fodder}} (\text{theoretical yield}_{\text{fodder}} \text{ (kg DM ha}^{-1} \text{ year}^{-1}\text{)} \times \text{FA}_{\text{fodder}} \text{ (ha)})} \times 100 \tag{7}$$

$$\text{IC maize (kg DM year}^{-1}\text{)} = \text{theoretical yield}_{\text{maize}} \text{ (kg DM ha}^{-1} \text{ year}^{-1}\text{)} \times \text{FA}_{\text{maize}} \text{ (ha)} \times \text{fodder yield correction (\%)} / 100 \tag{8}$$

$$\text{IC grass (kg DM year}^{-1}\text{)} = \text{theoretical yield}_{\text{grass}} \text{ (kg DM ha}^{-1} \text{ year}^{-1}\text{)} \times (\text{FA}_{\text{PG}} \text{ (ha)} + \text{FA}_{\text{TG}} \text{ (ha)}) \times \text{fodder yield correction (\%)} / 100 \tag{9}$$

Abbreviations are as follows: FA_{fodder}, the farm area of fodders (silage maize, permanent grasslands, and temporary grasslands); FA_{maize}, the farm area of silage maize, FA_{PG}, the farm area of permanent grasslands and FA_{TG}, the farm area of temporary grasslands. The mean CP content and yield of the fodder came from local institutes (Table 2). The amount of CP from grass production (GP) equalled the IC grass multiplied by its CP content:

$$\text{GP (kg CP year}^{-1}\text{)} = \text{IC grass (kg DM year}^{-1}\text{)} \times \text{CP}_{\text{grass}} \text{ (kg CP kg DM}^{-1}\text{)} \tag{10}$$

2.2.3 Consumption of human-edible feedstuff

To estimate the amount of human-edible crop feed protein (CfP_{he}) used by the dairy herd, we multiplied the amount of CP in feedstuffs (IC and purchased) by their respective hePF (Eq. 11) and DIAAS:

$$\text{CfP}_{\text{he}} \text{ (kg HDP year}^{-1}\text{)} = \sum_{\text{feeds}} (\text{quantity}_{\text{feed}} \text{ (kg DM year}^{-1}\text{)} \times \text{CP}_{\text{feed}} \text{ (kg CP kg DM}^{-1}\text{)} \times \text{hePF}_{\text{feed}} \text{ (\%)} / 100 \times \text{DIAAS}_{\text{feed}} \text{ (\%)} / 100) \tag{11}$$

We used the most recent and geographically close hePF, which came from Laisse et al. (2018) and Rouillé et al. (2023). They reflect the current use of food crops and by-products in the food sector in France. For gross efficiency, the amount of crop feed protein equalled the sum of the DM of the crops used multiplied by their respective CP content.

2.2.4 Land areas

Farm areas used by the dairy herd (i.e. permanent grassland, temporary grassland, and tillable land used to produce IC crops and maize silage) were described in the accounting data, while ‘imported’ areas (i.e. used to produce purchased

feeds) were estimated based on land competition coefficients (LC) from the ECOALIM (Wilfart et al. 2016) and AGRIB-ALYSE databases (Colomb et al. 2015). Although they are French references, they were valid for our farm sample as the Walloon region lies next to France. We assumed that purchased grass-based fodder came from temporary grasslands. Thus, permanent grassland area (A_{PG}) and temporary grassland area (A_{TG}) were calculated as follows:

$$A_{PG}(\text{ha}) = FA_{PG}(\text{ha}) \quad (12)$$

$$A_{CFP(\text{he})}(\text{ha}) = \sum_{\text{IC crops}} (FA_{\text{IC crops}}(\text{ha}) \times \text{hePF}_{\text{IC crop}}(\%)/100) + FA_{\text{maize}}(\text{ha}) \times \text{hePF}_{\text{maize}}(\%)/100 + \sum_{\text{purchased cropfeeds}} (\text{LC}_{\text{purchased cropfeed}}(\text{ha kg DM}^{-1}) \times \text{quantity}_{\text{purchased cropfeed}}(\text{kg DM}) \times \text{hePF}_{\text{purchased cropfeed}}(\%)/100) \quad (14)$$

$$A_{CFP(\text{nhe})}(\text{ha}) = \sum_{\text{IC crops}} (FA_{\text{IC crops}}(\text{ha}) * (1 - \text{hePF}_{\text{IC crop}}(\%))) + FA_{\text{maize}}(\text{ha}) \times (1 - \text{hePF}_{\text{maize}}(\%)/100) + \sum_{\text{purchased cropfeeds}} (\text{LC}_{\text{purchased cropfeed}}(\text{ha kg DM}^{-1}) \times \text{quantity}_{\text{purchased cropfeed}}(\text{kg DM}) \times (1 - \text{hePF}_{\text{purchased cropfeed}}(\%)/100)) \quad (15)$$

where $FA_{\text{IC crop}}$ and $\text{hePF}_{\text{IC crop}}$ are the farm area and the human-edible protein fraction of intra-consumed crops, respectively. FA_{maize} and $\text{hePF}_{\text{maize}}$ are the farm area and the human-edible protein fraction of maize silage.

The composition of compound feed was difficult to estimate because it varies throughout the year as a function of the availability and price of ingredients. As a result, we estimated the hePF, DIAAS, and LC of compound feed from a sample of 60 commercial recipes used by five commercial firms in the

$$A_{TG}(\text{ha}) = FA_{TG}(\text{ha}) + \text{LC}_{\text{purchased grass}}(\text{ha kg DM}^{-1}) \times \text{quantity}_{\text{purchased grass}}(\text{kg DM}) \quad (13)$$

FA_{PG} is permanent grassland area of the farm and FA_{TG} is the temporary grassland area of the farm. The human-edible crop feed protein area ($A_{CFP(\text{he})}$) and the non-human-edible crop feed protein area ($A_{CFP(\text{nhe})}$) are fictive area; they are associated with human-edible and non-human-edible shares of the protein of a crop. They were calculated as follows:

Walloon region from 2015 to 2021 for dairy cows ($n = 30$), young stock ($n = 24$), and calves ($n = 6$). We assumed that these parameters might vary as a function of the CP content in the compound feed, as protein-rich concentrates are often based on soya bean meal, which has a high LC and DIAAS (Hache 2015). The only significant linear correlations between the CP content of the compound feed and hePF, DIAAS, and LC were observed for dairy cows (Table 3). Consequently, we used the mean of each parameter for young stock and calves (Table 3).

Table 3 Estimated human-edible protein fraction (hePF), digestible indispensable amino acid scores (DIAAS), and land competition coefficients (LC) of compound feed for dairy cows, young stock, and calves. Linear regressions ($y = Bx + A$) as a function of the crude protein (CP) content (kg CP kg DM^{-1}) of concentrates was significant only for dairy cows. For the regressions' coefficients, the stand-

ard error (se) and significance of the difference from zero ($* < 0.05$, $** < 0.01$, and $*** < 0.001$) are shown. Root mean square error (RMSE), R^2 , and the coefficient of variation (CV) are shown for each linear regression. For young stock and calves, the estimates of hePF, DIAAS, and LC equalled mean values.

Group	Parameter	A (se)	B (se)	Mean (se)	RMSE	R^2	CV
Dairy cows	hePF (%)	7 (0.61)	60 (23)*		10.8	0.205	0.494
	DIAAS (%)	14 (6.9)	218 (27)***		123	0.715	0.183
	LC ($\text{m}^2 \text{kg DM}^{-1}$)	0.55 (0.072)***	1.80 (0.27)***		0.129	0.604	0.129
Young stock	hePF (%)			16 (1.1)			
	DIAAS (%)			60 (2.4)			
	LC ($\text{m}^2 \text{kg DM}^{-1}$)			1.05 (0.047)			
Calves	hePF (%)			25 (1.4)			
	DIAAS (%)			57 (4.3)			
	LC ($\text{m}^2 \text{kg DM}^{-1}$)			1.07 (0.056)			

2.3 Statistical analysis

2.3.1 Selection of influential farm characteristics

Using R (R Core Team 2021), we performed redundancy analysis (RDA) to select farm characteristics that significantly explained the metrics (Borcard et al. 2011). The farm characteristics tested were milk production per cow (kg FPCM cow⁻¹ year⁻¹), the percentage of maize silage in the fodder (%), concentrates per cow (kg DM cow⁻¹ day⁻¹), semi-concentrates (i.e. humid by-products and fodder beets) per cow (kg DM cow⁻¹), the CP content of concentrates (%), corrected fodder yield (%), stocking rate per unit of farm area (livestock units (LU) ha⁻¹), feed protein self-sufficiency (%), the age at first calving (months), the calving interval (days), and the number of female followers (i.e. replacement heifers and calves) per dairy cow (cow⁻¹). We began the RDA with all farm characteristics and removed the non-significant ones individually using backwards stepwise selection. Concentrates consisted of other IC crops, purchased crops, and compound feeds. Detailed descriptions of the farm characteristics are shown in Supplementary Material 1.

2.3.2 Sensitivity analysis

We performed sensitivity analysis of the estimated parameters to explore sources of uncertainty in the model. We varied each parameter by ± 1 standard error based on the mean CP content and yields of grass-based fodders and maize (Table 2); the mean hePF, DIAAS, and LC of compound feeds for young stock and calves; and the slope and intercept of the regressions between CP content and hePF, DIAAS, and LC for dairy cows (Table 3). Because estimated dairy cow DMI had a mean square error of 2.80 (Roseler et al. 1997), we used a root mean square error of 1.67 kg d⁻¹.

2.3.3 Cluster analysis

A Box-Cox transformation was applied to the data to normalise the distribution of the variables. To analyse the relation between net productivity and the existing metrics of

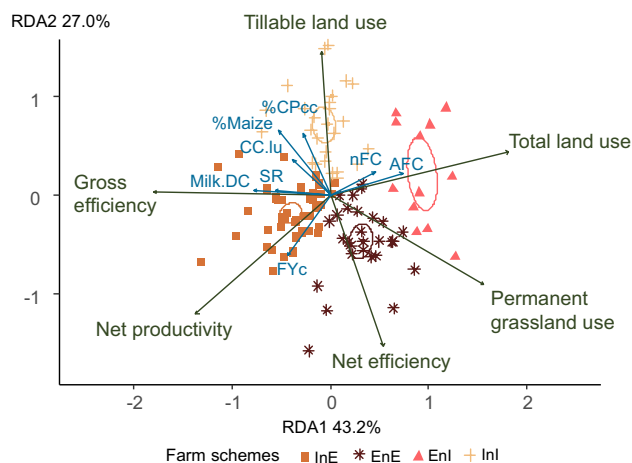


Fig. 3 Biplot of the first two components of the redundancy analysis (RDA) with projection of the metrics of contribution to food security and the farm characteristics that significantly explained the space defined by these metrics. Farm characteristic abbreviations are as follows: AFC: age at first calving, FYc: fodder yield correction, Milk.DC: milk production per dairy cow, SR: stocking rate, CC.lu: quantity of concentrates per livestock unit, %Maize: percentage of maize silage in the fodder, % CPcc: CP content of concentrates, nFC: number of female followers per cow. Ellipses represent the standard error of the centroid for each dairy farm strategy (InI: intensive net inefficient, InE: intensive net efficient, EnI: extensive net inefficient, and EnE: extensive net efficient), defined by *k*-means clustering of the metrics.

contribution to food security, we calculated the correlation between each pair of metrics (Pearson when normally distributed, or Spearman when not). To analyse the contribution of different dairy farm strategies to food security, we clustered farms using *k*-means clustering (non-hierarchical) based on the Euclidean distances among the six metrics (Borcard et al. 2011). The optimal number of clusters was determined using the indexes proposed by Charrad et al. (2014). Significant differences in farm characteristics and the six metrics between the clusters were analysed using analysis of variance when the variable was normally distributed (Shapiro-Wilk test > 0.05) and had homogeneous intra-group variance (Levene’s test > 0.05), or using a Kruskal-Wallis test when not. When the test showed a significant

Table 4 Pearson (P) and Spearman (S) correlation coefficients (when data were normally distributed or not, respectively) between metrics of contribution to food security. *ns* not significant, **p* < 0.05, ***p* < 0.01, and ****p* < 0.001.

	Gross efficiency	Net efficiency	Net productivity	Total land use	Permanent grassland use	Tillable land use
Gross efficiency	1	-0.12 ^{ns} (P)	0.63*** (P)	-0.75*** (P)	-0.69*** (S)	0.08 ^{ns} (S)
Net efficiency		1	0.38*** (P)	0.13 ^{ns} (P)	0.53*** (S)	-0.58*** (S)
Net productivity			1	-0.80*** (P)	-0.29** (S)	-0.40*** (S)
Total land use				1	0.57*** (S)	0.23* (S)
Permanent grassland use					1	-0.51*** (S)
Tillable land use						1

Table 5 Mean and standard error of the mean (SEM) of metrics of contribution to food security and the farm characteristics selected by redundancy analysis for the four clusters of dairy farms strategies: intensive and net efficient (InE), extensive and net efficient (EnE), intensive and net inefficient (InI), and extensive and net inefficient (EnI). For all variables, the analysis of variance, or

Mann-Whitney U test for non-normal distributions, was highly significant ($p < 0.001$). Different letters indicate significant differences among strategies. Abbreviations: *CP*: crude protein, *HDP*: human-digestible protein, *FPCM*: fat-and-protein-corrected milk, *LU*: livestock units, *DM*: dry matter. Metrics integrating the DIAAS are represented with a '**'.

	InE	EnE	InI	EnI	SEM
Metrics					
Number of farms	45	28	26	12	
Gross efficiency (kg CP kg CP ⁻¹)	0.201 ^a	0.169 ^c	0.188 ^b	0.134 ^d	0.0026
Net efficiency (kg HDP kg HDP ⁻¹)*	6.2 ^b	11.0 ^a	3.6 ^c	6.9 ^b	0.38
Net productivity (kg HDP ha ⁻¹)*	302 ^a	248 ^b	187 ^c	146 ^d	6.6
Total land use (m ² kg HDP ⁻¹)*	28.7 ^c	37.7 ^b	36.8 ^b	60.1 ^a	1.0
Permanent grassland use (m ² kg HDP ⁻¹)*	18.5 ^c	29.9 ^b	14.6 ^d	41.9 ^a	1.0
Tillable land use (m ² kg HDP ⁻¹)*	10.2 ^b	7.8 ^c	22.2 ^a	18.2 ^{ab}	0.81
Farm characteristics					
Milk production per cow (kg FPCM cow ⁻¹ year ⁻¹)	8106 ^a	6914 ^b	7842 ^a	5463 ^c	116
Stocking rate (LU farm ha ⁻¹)	2.38 ^a	2.19 ^a	2.30 ^a	1.53 ^b	0.054
Percentage of maize silage (%)	23 ^b	0 ^c	36 ^a	11 ^c	1.7
Concentrates per cow (kg DM cow ⁻¹ day ⁻¹)	4.6 ^a	3.8 ^b	4.9 ^a	3.1 ^b	0.15
CP of concentrates (%)	21.3 ^b	18.9 ^c	25.7 ^a	20.9 ^{bc}	0.39
Fodder yield correction (%)	116 ^a	110 ^a	89 ^b	82 ^b	1.9
Age at first calving (months)	27.6 ^c	30.2 ^b	30.4 ^b	34.9 ^a	0.31
Female followers per cow (cow ⁻¹)	0.78 ^b	1.37 ^a	1.01 ^a	1.08 ^a	0.076

difference, we used Tukey's range test when the data were normally distributed or a Mann-Whitney U test when not.

3 Results and discussion

3.1 Relationship between net productivity and existing metrics of contribution to food security

Correlations between metrics are presented in Table 4. Net productivity was significantly correlated with the five other metrics, positively with net efficiency (0.38) and gross efficiency (0.63) but negatively with total land use (-0.80), permanent grassland use (-0.29), and tillable land use (-0.40). Gross and net efficiencies show no correlation. Gross efficiency is negatively correlated with the total (-0.75) and permanent grassland use (-0.69), while net efficiency is positively correlated with the permanent grassland use (0.53) and negatively correlated with the tillable land use (-0.58). The total land use was positively correlated with both the permanent grassland (0.57) and the tillable land use (0.23).

3.2 The contribution of dairy system strategies to food security

The RDA showed that eight farm characteristics significantly explained (61.7%) the dataset of six metrics of contribution

to food security: milk production per cow (15.4%), quantity of concentrates per cow (12.2%), fodder yield correction (9.8%), percentage of maize silage in the fodder (9.3%), CP content of concentrates (8.6%), stocking rate (3.6%), number of female followers per dairy cow (1.7%), and age at first calving (1.2%). Only these farm characteristics are described further. A biplot of the two first components of the RDA, which explained 70.3% of the total variability in the metrics, was generated, along with the farm characteristics kept (Fig. 3).

The optimal number of clusters according to k -means clustering was four, as indicated by 12 of the 23 indicators proposed by Charrad et al. (2014). For the four clusters, the mean values, standard error of the mean (SEM), and statistical differences in the metrics and farm characteristics varied (Table 5). The distribution of the farms and standard error (ellipse) around the centroid of each cluster was generated on a biplot (Fig. 3). We associated the clusters with different strategies contributing to food security. The clusters are first named following the farms' performances in terms of land use (intensive/extensive) and secondly following their performances in terms of human-edible feeds use (net efficient/net inefficient). The cluster with the highest net productivity (302 kg HDP ha⁻¹) consisted of farms with an intensive and net efficient strategy (InE). It contained 40% of the farms and had, on average, the highest gross efficiency (0.201 kg CP kg CP⁻¹), an intermediate net efficiency (6.2 kg HDP kg HDP⁻¹), and the lowest total land use (28.7 m² kg HDP⁻¹). Mean permanent grassland and tillable

land uses were intermediate (18.5 and 10.2 m² kg HDP⁻¹, respectively). On average, this cluster had the highest fodder yield correction (116%), the fewest female followers per dairy cow (0.78 cow⁻¹), and the lowest age at first calving (27.6 months), associated with a high use of concentrates (4.64 kg DM cow⁻¹ day⁻¹) with an intermediate CP content (21.3%). The mean percentage of maize silage was also intermediate (23%).

The cluster with the second-highest mean net productivity (248 kg HDP ha⁻¹) contained 25% of the farms and exhibited an extensive and net efficient strategy (EnE). On average, it had the highest net efficiency (11.0 kg HDP kg HDP⁻¹), the second-lowest gross efficiency (0.169 kg CP kg CP⁻¹), intermediate total land use (37.7 m² kg HDP⁻¹), permanent grassland use (29.9 m² kg HDP⁻¹), and the lowest use of tillable land (7.8 m² kg HDP⁻¹). It had an intermediate age at first calving (30.2 months) and the second-lowest milk production (6914 kg FPCM cow⁻¹). These farms were entirely grass-based (no maize use), with a fodder yield correction similar to that of InE farms (110%) and the lowest amounts of concentrates (3.8 kg DM cow⁻¹ day⁻¹) and CP content of concentrates (18.9%). Two organic farms practiced the EnE strategy.

The third-highest net productivity (187 kg HDP ha⁻¹) was a cluster of 23% of the farms that had an intensive and net inefficient strategy (InI). On average, these farms had the second-highest gross efficiency (0.188 kg CP kg CP⁻¹) but the lowest net efficiency (3.6 kg HDP kg HDP⁻¹). Their total land use (36.8 m² kg HDP⁻¹) was intermediate. Their permanent grassland use was the lowest (14.6 m² kg HDP⁻¹), but they had the highest tillable land use (22.2 m² kg HDP⁻¹). Their milk production (7842 kg FPCM cow⁻¹) and concentrate use (4.94 kg DM cow⁻¹ day⁻¹) were similar to those of InE farms, but they used a higher percentage of maize silage (36%), had a higher CP content in concentrates (25.7%), and had a lower fodder yield correction (88.9%). Their age at first calving (30.4 months) was similar to that on EnE farms.

The last cluster contained 11% of the farms. On average, these farms had the lowest net productivity (146 kg HDP ha⁻¹), with an extensive and net inefficient strategy (EnI). Compared to EnE farms, these farms had a lower fodder yield correction (81.7%) and net efficiency (6.9 kg HDP kg HDP⁻¹). On average, this cluster had the lowest milk production (5493 kg FPCM cow⁻¹) and gross efficiency (0.134 kg CP kg CP⁻¹). They also had the highest total land use (60.1 m² kg HDP⁻¹), permanent grassland use (41.9 m² kg HDP⁻¹), and tillable grassland use (18.2 m² kg HDP⁻¹), but not significantly different from that of InI farms). Compared to EnE farms, EnI farms had similar CP content of concentrates (20.9%), percentage of maize silage in the fodder (11%), and quantity of concentrates per cow (3.10 kg cow⁻¹ day⁻¹). EnI farms had the lowest stocking

rate (1.53 livestock units ha⁻¹) and the highest age at first calving (34.9 months). Four organic farms practiced the EnI strategy. Compared to InE farms, EnE (1.37 cow⁻¹), InI (1.01 cow⁻¹), and EnI farms (1.08 cow⁻¹) had more female followers per dairy cow.

For the existing metrics, observed values were similar to published ones. The mean gross efficiency of dairy farm strategies ranged from 0.134 to 0.201 kg CP kg CP⁻¹ (Table 5), which is slightly lower than the 0.19 (extensive grass-based systems) and 0.24 (intensive maize-based systems) in France according to Laisse et al. (2018). For these two systems, Laisse et al. (2018) observed a net efficiency of 2.57 and 1.01 kg CP kg CP⁻¹, respectively, which is lower than our observations. However, they did not use DIAAS correction, which increases net efficiency, as animal products generally have higher protein digestibility and quality than plant products (Ertl et al. 2016a). Land use ranged from 28–60 m² kg HDP⁻¹, which agrees with the range of 33–59 m² kg CP⁻¹ estimated by de Vries and de Boer (2010) for dairy systems without DIAAS correction.

The ranking of the farm strategies depended on the metric used to represent their contribution to food security (Table 5), which hinders identification of a best-performing system. Farms with a high efficiency of human-edible protein use (net efficiency) can have a low efficiency of agricultural land use (high total land use), such as the EnI strategy. Although we did not observe a significant correlation between net efficiency and total land use (Table 4), other studies observed a correlation of -0.7 (Mosnier et al. 2021). However, this was in the case of beef systems, which are hardly comparable with dairy systems in terms of feed conversion efficiency. The net productivity metric developed can help capture the insight of feed conversion efficiency, as it was positively correlated with both gross and net efficiency, as well as the insight of the efficiency of agricultural land use, as it was negatively correlated with the use of total land, permanent grassland, and tillable land (Table 4).

The strategy that had the highest net productivity (InE) had farm characteristics that increase the gross and net efficiency of protein use, as well as the efficiency of agricultural land use. First, InE farms had an appropriate percentage of maize silage in the fodder and a lower mean CP content of concentrates than farms in the other intensive strategy (InI). Maize silage competes in part with human food (Laisse et al. 2018) and needs to be supplemented with concentrates with a higher CP content to compensate for having a lower CP content than grass (Table 2). The use of concentrates with a higher CP content influences the animal systems' contribution to food security, as they had a higher hePF, DIAAS, and LC (Table 3). This is because CP-rich concentrates in Europe usually include some soya bean meal (Hache 2015), which is considered to compete with human food (Mottet et al. 2017).

Second, InE farms had the fewest female followers per dairy cow and the lowest age at first calving. As heifers represent an unproductive phase in the lives of dairy cows, adapting the number of heifers more precisely to the desired rate of herd renewal and reducing the age at first calving can increase gross efficiency of feed use at the herd level (Vandehaar 1998). A high milk production, as shown by InE farms, also increases the gross efficiency as the metabolic maintenance and gestation needs are diluted (Vandehaar 1998). However, increasing the growth of heifers and milk production may be at the expense of contribution to food security if more human-edible feedstuffs are used to reach those performances. The issue is ‘how much is too much?’. Wilkinson and Lee (2018) explained the advantage of using appropriate amounts of concentrates to supplement unbalanced fodder-based diets of dairy cows; thus, it would be interesting to explore the marginal yield (i.e. the additional output resulting from a one-unit increase in the use of a variable input) of one human-edible feed protein on AFP production in different circumstances.

We observed that using semi-concentrates had no influence, probably because farmers do not use them often in this form but mostly in the form of compound feed. The use of industrial by-products is often highlighted as a key argument for the recycling function of livestock in the food system (Wilkinson 2011; Ertl et al. 2016b; Laisse et al. 2018; Wilkinson and Lee 2018; van Zanten et al. 2019). However, by-products are finite resources for which competition is increasing, especially due to the development of bioenergy production (Muscat et al. 2020). For organic farms, this option is complicated, as few by-products are certified as organic. As a result, organic farms tend to produce their own concentrates from cereals or pulses (Faux et al. 2021), which could decrease net efficiency. Our results indicate that four and two organic farms had an EnI or EnE strategy, respectively, which shows that organic farms can have low or high net efficiency, respectively. A larger sample of organic farms could provide greater insight into this specific type of farming system.

InE farms had high fodder yields, which resulted in the lowest total land use and permanent grassland use of the four strategies. This highlights the need to manage grass resources efficiently to increase the contribution of ruminant systems to food security (Wilkinson and Lee 2018). Even though it has not been approached in this study, this efficient management of grass also considers grass quality which can highly vary in function of the grassland species, fertilisation, pasture, and mowing management (Baumont et al. 2009). Grass quality is crucial as it can enable the reduction of CP content in the concentrates. InE farms had intermediate tillable land use, which could likely be reduced to increase production of food crops. However, the extent to which it must be reduced is not clear, as mixed crop-livestock systems have been

found to be environmentally and economically sustainable (Ryschawy et al. 2012). For example, certain feed products (e.g. catch crops, temporary grasslands) can be added to a food-crop rotation to maintain fertility and reduce pest pressure (Hoeffner et al. 2021). Conversely, some permanent grasslands can likely be cultivated (Hennessy et al. 2021), but this was not considered in our study.

3.3 Sensitivity and adaptability of the metric of net productivity

This study shows some limitations inherently due to the use of accounting data, as those are not measured on farm but derive from CAP-declaration, invoice and farmers’ words. However, we tried to reduce the uncertainty of our dataset by having it checked by the farm advisors. As some data was lacking, e.g. fodders quality and quantity, we used local references and performed a sensitivity analysis to assess the impact of uncertainty around these references on our results. In this sensitivity analysis, results for each dairy strategy did not differ significantly ($p > 0.05$) from the baseline scenario, which indicated that they were robust. The most influential parameter was the hePF of concentrates for the InE strategy ($p < 0.10$). In the future, this sensitivity to feed hePF could be a disadvantage, especially for the InE strategy, which uses relatively large amounts of concentrates per cow. As Laisse et al. (2018) indicated, the hePF is not fixed or generalisable. Potential scenarios (Ertl et al. 2015; Laisse et al. 2018) show that the hePF of feedstuff will increase due to new and more efficient technological processes and changes in consumption habits.

The definition of systems with optimal net productivity must be contextualised, as an InE strategy cannot be applied to every situation. When no tillable land is present, the EnE strategy is an interesting alternative to the InE strategy because it still has high efficiency of using human-edible protein. Furthermore, some soil and climate conditions can decrease fodder yields, which decreases net productivity. At this stage, it is not clear which farms can increase their fodder yields under their specific soil and climate conditions. Future research could estimate potential fodder yields to provide information about the yield gap and the room for improvement, especially for EnE and EnI farms. However, intensifying grassland management, as on InE farms, can cause environmental impacts such as acidification, eutrophication, and climate change related to the use of mineral N (Haas et al. 2001) impacting supporting and regulating ecosystem services (Paudel et al. 2023). As a result, target performances for net productivity should consider the other dimensions of farm sustainability to identify strategies that can optimise sustainable food security (Godfray and Garnett 2014).

4 Conclusion

Our objective was to develop a metric that can be used to quantify the contribution of dairy systems to the food availability dimension of food security by considering both the use of human-edible protein and agricultural land at the same time. As hypothesised, this new metric, net productivity, was positively correlated with metrics of feed conversion efficiency (gross and net) and negatively correlated with the efficiency of agricultural land use (total land, permanent grassland, and tillable land). In an absolute way, net productivity highlights intensive and net efficient dairy systems that have high milk production per cow and fodder yield, intermediate use of maize silage and CP content of concentrates, and efficient management of followers. However, these systems are the most sensitive to an increase in the human-edible fraction of the feeds used. Target performances of net productivity should consider additional aspects of sustainability to manage trade-offs while considering local soil and climate constraints. Future studies could calculate net productivity for other animal systems and explore the results for other nutritional aspects, such as energy content.

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Data availability The datasets analysed in the current study are not publicly available due to a confidentiality clause with the participating organisations.

Code availability Upon reasonable request, the statistical models are available from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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