



OPEN Quantifying the stability of food supply and assessing the impact of milk quota removal in Walloon specialized dairy systems

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Compared to other systems, intensive grass-based dairy systems are known to maximize their contribution to food availability, represented by the metric of net productivity. This study analysed whether these systems also have the highest stability of supply, another crucial dimension of food security. To represent this aspect, we used the annual production resilience indicator (R_p), especially developed for agricultural production data, on gross and net productivity based on accounting data from 79 specialised dairy systems in the Walloon region of Belgium from 2011 to 2020. We grouped the farms into three representative farm types using k-means clustering. The results indicated that the intensive grass-based type also had the highest net productivity resilience. While providing a lower mean net productivity, the extensive grass-based type is characterized by a higher net productivity resilience compared with the intensive maize-based type. The end of milk quotas in 2015 was associated with a decrease in the resilience of gross and net productivity for all farm types due to type-specific changes in farm characteristics. This analysis provides a benchmark for other animal production systems. R_p focuses on production resilience but could be integrated in wider assessments of socio-ecological resilience.

The demand for animal food products is expected to increase due to the rise in the human population and the higher amount of meat, milk and eggs included in human diets worldwide¹. As livestock currently use 0.84 billion t of human-edible feed and 1.2 billion ha of arable land² the associated expansion of livestock farming threatens global food security. For the food security dimension of food availability³ several metrics have been developed to quantify the performances of animal production systems. Historically, the metric of gross productivity, which represents the amount of animal food produced per unit area, has been used⁴. However, due to the growing concern about feeding human-edible ingredients to livestock⁵ net productivity is a newly developed metric that considers the use of human-edible feed and agricultural land to represent more consistently the contribution of animal production systems to food availability⁶. Based on the ecological concept of net productivity⁷ it represents the net amount of food products that animals (lower trophic level) provide to humans (higher trophic level) per unit of time and space. Previous results for specialised dairy farms in Wallonia (Belgium) show that farms that maximise net productivity are intensive and grass-based⁶. However, this is not necessarily the most reliable system for the stability of supply, which is another crucial dimension of food security that should be analysed³.

More precisely, the stability of supply is the ability of agricultural systems to maintain (food) production during disturbances, which can be linked to the concept of resilience⁸. First described by Holling in an ecological framework in 1973, resilience “determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist”. The persistence of such an ecosystem through shocks can be represented by its vegetal primary production⁹ or animal density¹⁰. Based on this ecological perspective, previous analyses of agricultural resilience have used production indicators derived from the mean and inter-annual variability of yields, such as the production resilience indicator (R_p)¹¹. In engineering, resilience refers to the ability of a system to return to an equilibrium state after a perturbation¹². Notably, R_p aligns with both the ecological and engineering definitions of resilience⁸. Over time, the concept of resilience has evolved to encompass socio-ecological systems¹³ by incorporating human and institutional dimensions. A comprehensive definition of farming system resilience is “the ability

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to ensure the provision of system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability, and transformability¹⁴. This broader approach emphasizes the role of social dynamics, including learning, innovation, and self-organization¹³. Even though these definitions are relatively clear, they do not provide a direct methodology to measure resilience¹⁵.

One way to quantify production resilience would be to perform time-series analysis, which can assess changes in the stability of production over time and potentially predict threatening regime shifts¹⁶. In this context, the most popular approaches assess changes in the variance and temporal autocorrelation of production over time¹⁷. Temporal autocorrelation can be a more robust indicator of regime shift than variance¹⁸ but it must be calculated using high-frequency data on production¹⁹. However, agricultural data do not usually have such high frequency, being available usually at an annual time step, and inter-annual anomalies (difference to a long-term mean) are rarely autocorrelated¹¹. As a result, Zampieri et al. specifically designed the production resilience indicator (R_p) for agricultural time-series and applied it to crop production¹¹. This indicator is now officially included as *Context and Impact Indicator* in the current Common Agricultural Policy (CAP, I.9)²⁰ using total cereal production of European countries as proxy of basic agricultural production, while the stability of animal related products is not considered yet.

Assessing the production resilience of Walloon dairy systems can be performed as a case study to inspire larger scale analyses. However, it is also urgently needed as Walloon dairy systems are increasingly challenged by environmental stresses as well as political and economic changes. On the one hand, climate variability is impacting fodder production by increasing the frequency of extreme weather events²¹. As a result, Walloon farmers stated that they had experienced “their best and worst year” in the past five years. For example, Wallonia experienced an extreme drought in 2022, with a mean rainfall deficit of 86% in July and August²². This decreased the amount and quality of fodder, and ultimately milk production²³. On the other hand, milk quotas in the European Union ended in April 2015, which has increased the exposure of dairy farmers to the price volatility of the free market²⁴. Consequently, since 2000, the lowest and highest milk price paid to farmers (28.1€ and 55.1 € per 100 l in 2016 and 2022, respectively) were observed after 2015²³. This led farmers to adapt their management practices in response to low prices (e.g. reduce concentrate use)²⁵ and high prices (e.g. continue to milk older, less productive cows)²³ which influences total milk production of the farm.

To increase competitiveness when the quotas were in place, dairy farms implemented structural changes, especially intensifying milk production and increasing farm size. Now that milk quotas have ended, dairy farmers are expected to increase this trend to keep up with international prices²⁶. In Wallonia, the number of dairy farms decreased from ca. 19,000 at the beginning of the quotas (1984) to 5,000 at the end (2015), and an additional 2,000 dairy farmers have abandoned farming since then. The mean amount of milk delivered per farm has increased, and is currently 515 kl/year, which is ca. 10 times as much as that in 1984²³. This intensification of dairy farms could come at the expense of resilience²⁷. For example, interviews with farmers indicate that specialised intensive dairy farms were more sensitive to the COVID-19 crisis²⁸. In addition, according to stakeholders' views of intensive European farming systems, including Belgian dairy systems, the strategies used to increase efficiency have decreased positive impacts on private functions, such as economic viability but also resilience, but increased negative impacts on public functions, such as preserving biodiversity and natural resources. Thus, although some extensive systems can still benefit from intensification, these systems should identify alternative strategies to increase their resilience²⁹. However, few quantitative studies exist on the resilience of dairy systems.

The objectives of the present study was to assess the resilience of the contribution to food security of dairy systems using the production resilience indicator and compare the traditional metric of gross productivity to the new metric of net productivity. More specifically, we grouped multiple farms into more general types of production systems based on their degree of intensification and other related characteristics, and compared the resilience of their gross and net productivity. We also explored the influence of the end of milk quotas on the resilience of both metrics.

Materials and methods

Production data

We used farm accounting data to calculate the annual gross (Eq. 1) and net (Eq. 2) protein productivity⁶ of specialised dairy farms in the Walloon region (Belgium) over 10 years (2011–2020). Out of 557 farms for which data were available, only the 79 that had data for all 10 years were used. The data came from two agricultural advisory organisations – the Walloon Department of Agricultural Economic Analysis ($n=49$ farms) and the Walloon Breeders Association (Elevéo: $n=30$ farms) – and covered a wide variety of specialised dairy systems.

$$\text{Gross productivity} : \frac{AFP}{APG + ATG + ACfP_{(nhe)} + ACfP_{(he)}} \quad (1)$$

$$\text{Net productivity} : \frac{AFP - CfP_{he}}{APG + ATG + ACfP_{(nhe)}} \quad (2)$$

with AFP : animal-food protein; CfP_{he} : human-edible protein used as feed; $ACfP_{(he)}$: crop area needed to produce human-edible protein used as feed; $ACfP_{(nhe)}$: crop area needed to produce non-human-edible protein used as feed; ATG : temporary grassland area; APG : permanent grassland area.

Although both gross and net productivities can be expressed in terms of energy, this study focuses on protein, as it is a key component of animal food products for human nutrition³⁰. The amount of AFP equalled the sum of meat and milk protein produced and sold. AFP and CfP_{he} were corrected by multiplying them by the digestible indispensable amino-acid score³¹ for meeting the nutritional needs of a child 6 months to 3 years old³². To

calculate the amount of human-edible protein used as feed, we used the most recent and geographically close human-edible protein fractions, which reflects the current use of food crops and by-products in the French food sector^{33,34}. The area used to produce each imported feedstuff was obtained from the ECOALIM³⁵ and AGRIBALYSE³⁶ databases. See Battheu-Noirfalise et al. (2023)⁶ for a description of the full model.

Annual production resilience indicator

The resilience of gross and net productivity was represented by the annual production (P) resilience indicator R_p (Eq. 3), specifically developed for annual agricultural production systems³⁷:

$$R_p = \frac{\text{mean}(P)^2}{\text{variance}(P)} \quad (3)$$

If stability can be measure by the coefficient of variance, then the production resilience can be defined as the squared stability according to Eq. 3. R_p was derived mathematically from the ecological definition of resilience, as the “the largest disturbance that the system can absorb before it loses its normal functioning”¹⁰. Assuming that the amplitude of the disturbance is correlated with the magnitude of the production anomalies, and that the larger disturbance are more rare than the smaller ones, then resilience can be simply measured statistically as the return period of large production anomalies, which is defined as the mean time that elapses between production anomalies of a given amplitude. It has been shown that R_p is proportional to the return period of such anomalies¹¹. Moreover, albeit defined on the recorded annual production data, R_p is also sensitive to intraseasonal perturbations and fully consistent with the engineering definition of resilience as well⁸. Therefore, it is the most robust and applicable diagnostic indicator of production resilience for agricultural data as other popular indicators such as the temporal autocorrelation require higher frequency time-series^{16,19}. It is worth noting that, for certain agricultural systems such as crops, temporal autocorrelation of production data would often be zero due to annual seeding.

In this study, we applied for the first time the R_p indicator to dairy system data. As R_p can be calculated only for positively defined time-series such as gross production, it is in principle not possible to calculate it for negative values of net productivity, which could occur when the amount of human-edible feed consumed exceeds the amount of AFP produced. In practical terms, this limitation is consistent with the irrelevance of calculating the resilience of a negative contribution to food security and it was not encountered in our time-series analysis. However, the potential for many types of animal production to have negative net productivity formally limits application of R_p . This issue must be considered is net productivity is used instead of gross productivity, ensuring that no negative numbers are found in the time-series.

Statistical analysis

Classification of farm production systems

To group individual farms into the main types of dairy production in the Walloon region, we applied principal component analysis (PCA) followed by cluster analysis (CA)³⁸. The PCA was used to reduce the number of dimensions into a few principal components (PC). The number of PC retained was determined using Kaiser's criterion, which retains only PC with an eigenvalue > 1. The CA was performed using a non-hierarchical k-means algorithm based on Euclidean distances³⁹ of the 10-year mean of nine farm characteristics that had a significant influence on the metrics of contribution to food security⁶: milk production per cow, fodder yield, percentage of maize silage in the fodder, amount of concentrates fed per cow, CP content of concentrates, stocking rate, age at first calving and the number of replacement heifers per cow. The fodder yield was expressed as a percentage of regional mean yields. The optimal number of clusters was determined using the NbClust package, which calculates 30 indices from all combinations of clusters⁴⁰. Differences in farm characteristics and gross and net productivity among clusters were analysed using a linear mixed model (LMM) with the cluster as a fixed effect and the year and the farm ID nested in the cluster as random effects. The last factor was used to consider potential effects of autocorrelation of individual farms among years⁴¹. Differences in farm characteristics and metrics of contribution to food security among the clusters were tested using Type II analysis of variance followed by Tukey's range test. All statistical analyses were performed using R software (version 4.2.2)⁴².

Estimating annual production resilience for the farm types and periods

We calculated the annual production resilience indicator for each cluster using farm-standardised data (i.e. the 10 years of data per farm, divided by their mean). This approach enabled the resilience of different production systems to be calculated and also provided a sample size sufficiently large to calculate R_p reliably¹¹. We used a Monte Carlo method to estimate the error in the R_p of each cluster by randomly sampling from a Gaussian distribution with the same mean and variance. A significance level of 0.05 was chosen to assess differences between clusters¹¹. This method was applied to each period (before or after the end of milk quotas) separately to assess the influence of the end of milk quotas on the resilience of gross and net productivity. We also analysed the difference in farm characteristics between the two periods to analyse their relation to the resilience of productivity. Differences in gross productivity, net productivity and farm characteristics between these periods were analysed using a LMM, by creating a new binary variable (“Quota”) in which 2011–2015 was “Before” and 2016–2020 was “After”. The LMM used the cluster and the Quota as fixed effects and the farm ID nested in the cluster as a random effect. The variable “year” was not included in the LMM as it was entirely defined by “Quota”. All models were fitted using the package lme4 (version 1.1–31) of R⁴³.

Results

Cluster analysis

The first three PC of the PCA were included in the clustering (eigenvalue > 1) (Fig. 1). The optimal number of clusters was three, as determined by the largest number of indices in the NbClust package (7/30). The clusters were named for their degree of intensification and the main forage used to feed the cows (i.e. maize silage or grass) (Table 1).

The first cluster ($n=29$) represented an intensive and grass-based farm type (IG). On average, it had high milk production per cow (7580 FPCM $\text{cow}^{-1} \text{year}^{-1}$) and stocking rate (2.3 LU ha^{-1}), with little use of maize silage (6%). As a result, IG used a high percentage of grass-based fodder and fed large amounts of concentrates (4.8 kg DM $\text{cow}^{-1} \text{day}^{-1}$), but with a low CP content (19.8%). IG had a low age at first calving (29.2 months) and 0.75 female followers per dairy cow. IG had the highest fodder yield (116%) and contained 0.5% organic farms.

The second cluster ($n=16$) represented an intensive and maize-based farm type (IM). It had the highest milk production per cow (7670 FPCM $\text{cow}^{-1} \text{year}^{-1}$) and stocking rate (2.6 LU ha^{-1}) (albeit not different from those of IG). It used the highest percentage of maize silage in the fodder (38%). IM fed a large amount of concentrates (4.2 kg DM $\text{cow}^{-1} \text{day}^{-1}$), similar to that of IG, but with a higher CP content (26.3%). IM had a relatively low age at first calving (30.3 months) and the most replacement heifers per cow (0.88). IM had a fodder yield slightly below the mean regional yields of grass and maize silage (97%) and contained no organic farms.

The third cluster ($n=36$) represented an extensive and grass-based farm type (EG). It had the lowest milk production per cow (5480 kg FPCM $\text{cow}^{-1} \text{year}^{-1}$) and stocking rate (1.7 LU ha^{-1}). It used a percentage of maize silage similar to that of IG (9%) and fed the smallest amount of concentrates (2.3 kg DM $\text{cow}^{-1} \text{day}^{-1}$), with a CP content of 19.8%. EG had the highest age at first calving (33.6 months) and the fewest replacement heifers per cow (0.63). EG had a fodder yield (91%) similar to that of IM and contained 9.2% organic farms.

Gross and net productivity resilience over 10 years

IG and IM did not differ in gross productivity, but IG had higher net productivity than IM (269 and 231 kg HDP ha^{-1} , respectively) (Table 2). EG had the lowest gross and net productivities (199 and 183 kg HDP ha^{-1} , respectively). IG had the highest resilience of gross and net productivity (80.9 and 52.8, respectively). IM had higher resilience of gross productivity than EG (53.3 and 48.5, respectively), but EG had higher resilience of net productivity than IM (42.9 and 20.5, respectively). Although IM had higher mean net productivity, the variance

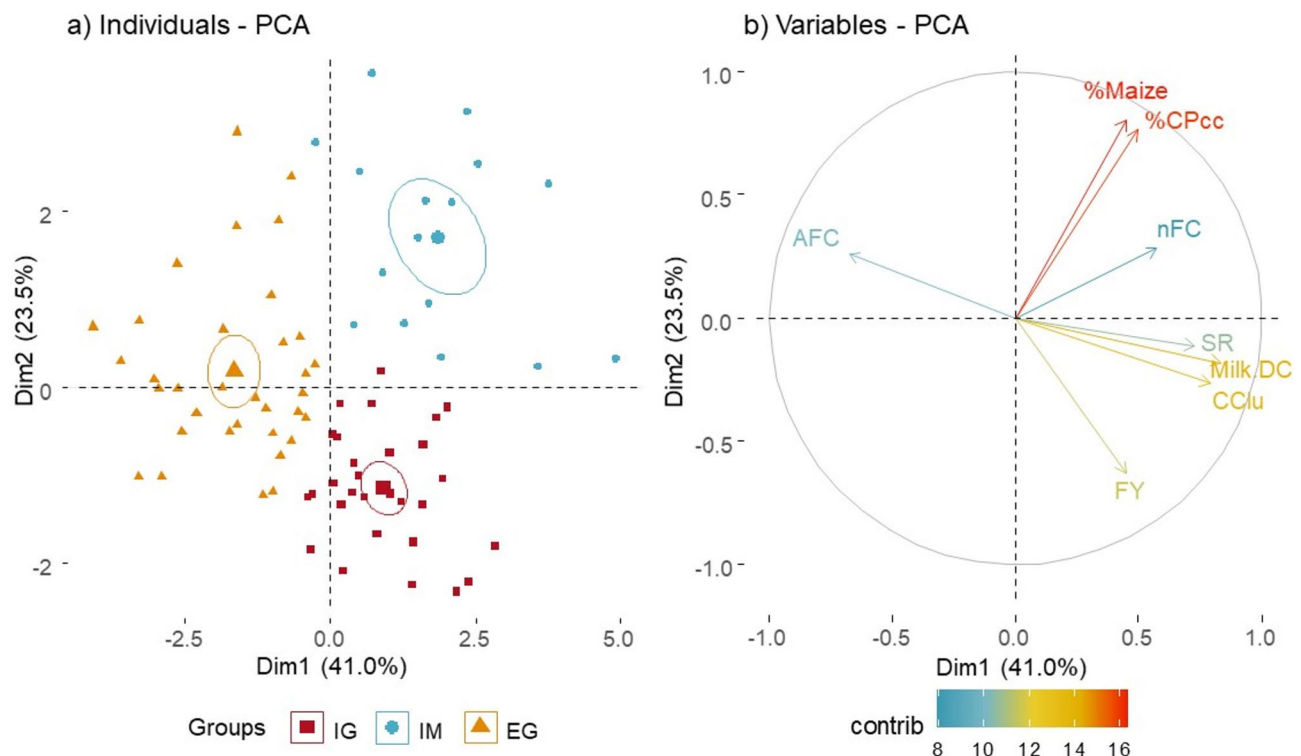


Fig. 1. Biplot of the first two components of the principal component analysis (PCA) of the 10-year mean per farm of farm characteristics, showing the (a) individual farms and (b) variables of characteristics. Abbreviations: AFC: age at first calving, FY: fodder yield, Milk.DC: milk production per dairy cow, SR: stocking rate, CC.lu: amount of concentrates fed per livestock unit, %Maize: percentage of maize silage in the fodder, % CPcc: crude protein content of concentrates and nFC: number of replacement heifers per cow. Ellipses represent the standard error of the centroid for each dairy farm type (intensive grass-based (IG), intensive maize-based (IM) and extensive grass-based (EG)), based on k-means clustering of farm characteristics.

Characteristic	Farm types			SEM
	IG	IM	EG	
Number of farms	29	16	34	
Milk production per cow (kg FPCM cow ⁻¹ year ⁻¹)	7580 a	7670 a	5480 b	180
Fodder yield (%)	116 a	97 b	91 b	2.3
Percentage of maize silage (%)	6 b	38 a	9 b	1.9
Concentrates fed per cow (kg DM cow ⁻¹ day ⁻¹)	4.8 a	4.2 a	2.3 b	0.18
CP content of concentrates (%)	19.8 b	26.3 a	19.8 b	0.39
Stocking rate (LU ha ⁻¹)	2.33 a	2.62 a	1.69 b	0.075
Age at first calving (months)	29.2 b	30.3 b	33.6 a	0.41
Replacement heifers per cow (cow ⁻¹)	0.75 b	0.88 a	0.63 c	0.021
Percentage of organic farms (%)	0.5	0.0	9.2	

Table 1. Mean and standard error of the mean (SEM) of farm characteristics and the percentage of organic farms of the three types of dairy farms defined based on k-means clustering of farm characteristics: intensive grass-based (IG), intensive maize-based (IM) and extensive grass-based (EG). Differences among all variables in the analysis of variance were significant ($p < 0.001$). Different letters indicate significant differences among farm types. Abbreviations: FPCM: fat-and-protein-corrected milk, DM: dry matter, CP: crude protein, LU: livestock units. Fodder yield is expressed as a percentage of regional means of grass and maize silage yields.

Metric or indicator	Farm types		
	IG	IM	EG
Gross productivity (kg HDP ha ⁻¹)	302 ± 52 a	301 ± 68 a	199 ± 51 b
Net productivity (kg HDP ha ⁻¹)	269 ± 56 a	231 ± 62 b	183 ± 50 c
Resilience of gross productivity	80.9 a	53.3 b	48.5 c
Resilience of net productivity	52.8 a	20.5 c	42.9 b

Table 2. Mean gross and net productivity and their resilience for the three farm types: intensive grass-based (IG), intensive maize-based (IM) and extensive grass-based (EG). Differences among all variables in the analysis of variance were significant ($p < 0.001$). Different letters indicate significant differences among farm types. This was tested using a linear mixed model for means of gross and net productivity and a Monte Carlo method for their resilience. Abbreviation: HDP: human-digestible protein.

in net productivity (standard deviation (SD)=62 kg HDP ha⁻¹) was larger than that of EG (SD=50 kg HDP ha⁻¹), which decreased its resilience.

According to the LMM that predicted gross productivity, the cluster explained 52.6% of the variance, the farm ID nested in the cluster explained 33.1%, and the year explained only 1.2%; the remainder (13.1%) was residual variance. According to the LMM that predicted net productivity, the cluster explained 37.6% of the variance, the farm ID nested in the cluster explained 38.1%, and the year explained only 1.6%; the remainder (22.7%) was residual variance.

Resilience of gross and net productivity before and after the end of milk quotas

After the end of quotas, IG showed no significant change in gross or net productivity, but their resilience decreased (from 92.6 to 90.8 and 62.7 to 53.1, respectively) (Table 3) because their variance increased (SD from 44 to 50 and 46 to 53 kg HDP ha⁻¹, respectively). This was associated with an increase in milk production and concentrates fed per cow and a decrease in stocking rate and the CP content of concentrates (Table 4). Similarly, after the end of quotas, IM showed no significant change in gross or net productivity, but their resilience decreased significantly (from 63.9 to 56.4 and 23.5 to 18.0, respectively). This was associated with an increase in milk production, fodder yield and concentrates fed per cow and a decrease in the age at first calving and number of female followers per cow. In contrast, after the end of quotas, EG showed a significant decrease in gross and net productivity (from 212 to 185 and 195 to 170 kg HDP ha⁻¹, respectively) and in their resilience (56.1 to 49.5 and 49.1 to 42.7, respectively). This was associated with a decrease in stocking rate and an increase in age at first calving and number of female followers per cow.

Discussion

Advantages and limitations of the production resilience indicator

This study is the first to use farm accounting data to show the utility of the annual production resilience indicator (R_p) for quantifying the *stability of supply* dimension of food security. Doing so, this study contributes to the European Commission’s request to quantify and operationalise farm resilience⁴⁴ and complements the use of the R_p indicator that is already routinely adopted to measure the progress of European Member States (MS) in the context of the current CAP implementation²⁰. In addition, this study highlights the possibility of analysing

Metric or indicator	Farm types								
	IG			IM			EG		
	Before	After	P	Before	After	P	Before	After	P
Gross productivity (kg HDP ha ⁻¹)	306 ± 44	298 ± 50	ns	297 ± 51	305 ± 71	ns	212 ± 45	185 ± 48	< 0.001
Net productivity (kg HDP ha ⁻¹)	272 ± 46	266 ± 53	ns	236 ± 41	227 ± 55	ns	195 ± 43	170 ± 47	< 0.001
Resilience of gross productivity	92.6	90.8	< 0.001	63.9	56.4	< 0.001	56.1	49.5	< 0.001
Resilience of net productivity	62.7	53.1	< 0.001	23.5	18.0	< 0.001	49.1	42.7	< 0.001

Table 3. Mean gross and net productivity and their resilience before (2010–2015: “Before”) and after (2016–2020: “After”) the end of milk quotas for the three farm types: intensive grass-based (IG), intensive maize-based (IM) and extensive grass-based (EG). Differences between the two periods were tested using a linear mixed model for means of gross and net productivity and a Monte Carlo method for their resilience. Abbreviation: HDP: human-digestible protein, ns: non-significant ($p > 0.05$).

Item	Farm types								
	IG			IM			EG		
	Before	After	P	Before	After	P	Before	After	P
Milk production per cow (kg FPCM cow ⁻¹ year ⁻¹)	7490	7660	< 0.05	7470	7870	< 0.001	5530	5440	> 0.05
Fodder yield (%)	117	115	> 0.05	92 b	102	< 0.001	92	91	> 0.05
Percentage of maize silage (%)	7	5	> 0.05	39	38	> 0.05	10	9 b	> 0.05
Concentrates fed per cow (kg DM cow ⁻¹ day ⁻¹)	4.6	5.0	< 0.005	4.0	4.4	< 0.05	2.4	2.2	> 0.05
CP of concentrates (%)	20.4	19.3	< 0.05	26.0	26.5	> 0.05	20.1	19.4	> 0.05
Stocking rate (LU ha ⁻¹ farm ⁻¹)	2.39	2.26	< 0.001	2.56	2.67	> 0.05	1.75	1.62	< 0.001
Age at first calving (months)	29.2	29.2	> 0.05	30.8	29.7	< 0.05	33.0	34.3	< 0.001
Female followers per cow (cow ⁻¹)	0.75	0.75	> 0.05	0.94	0.83	< 0.001	0.58	0.69	< 0.001

Table 4. Mean farm characteristics before (2010–2015: “Before”) and after (2016–2020: “After”) the end of milk quotas for the three farm types: intensive grass-based (IG), intensive maize-based (IM) and extensive grass-based (EG). Abbreviations: FPCM: fat-and-protein-corrected milk, DM: dry matter, CP: crude protein, LU: livestock units. Fodder yield is expressed as a percentage of regional means of grass and maize silage yields.

the food availability dimension of food security not only by considering the gross farm production, but also by considering the use of human-edible feedstuffs. However, a prerequisite of this analysis needs a preliminary checking for negative values, which would invalidate the R_p calculation (see Methods). We found that net productivity of dairy systems was lower than gross productivity, and the resilience of net productivity was also lower than that of gross productivity. Farm characteristics of each type explained more of the variance in gross productivity than that in net productivity, while farms nested in the cluster explained more of the variance in net productivity. This could be because, although intensification increases gross and net productivity, for a given degree of intensification, individual farms’ choice of feedstuffs influences net productivity strongly.

In this study, we applied R_p to farm accounting data of dairy systems, as these data, like those of annual crop production, can help quantify the influence of intra-seasonal disturbances on anomalies in annual milk and meat production. However, unlike annual crops, the same cow can produce milk for several years. Thus, production anomalies might be expected to persist for more than one year, but this would imply that a sick or injured cow had not been treated after one year, which is seldom the case. R_p can also consider trends in a production time series due to factors that can influence the mean and variance, such as technological development, genetic selection or improved management¹¹. In this study, however, we did not have a sufficiently long time series to consider this aspect. One advantage of the method is that it can be easily applied to obtain insights into the resilience of production in the European livestock sector, using the presented methodology on FADN data. Although, the resilience of production indicator requires only annual data, thus less data than approaches such as temporal autocorrelation, as discussed elsewhere⁴⁵ quantifying resilience requires large amounts of data, and only 14% of the farms provided by the two accounting organisations for the present study had a full 10-years dataset. One limitation of this study is that it considered only five years before and after the end of milk quotas.

Resilience remains a fuzzy concept, for which many definitions and methods have been developed⁴⁶. The present study focused on the ecological and engineering definitions of resilience, which can be represented through the ecosystem’s production functions⁴⁷. In this context, the study assumes that, despite shocks and stresses, food supply should remain stable. This aligns with the question “resilience for what purpose ?” posed by Meeuwissen et al. (2019) in their resilience assessment framework¹⁴. In this matter, R_p is the only resilience indicator specifically designed for annual agricultural time-series analyses that is rigorously based on clear assumptions. However, it has not yet been extensively tested, and as a purely diagnostic indicator, it requires cross-checking with other factors to accurately interpret the causes of observed resilience values and their changes. Although our approach centers on production at the farm level and is therefore narrower than a

socio-ecological perspective, it can nonetheless be integrated into broader frameworks that incorporate other quantitative indicators⁴⁵ as well as qualitative aspects such as farmers' perceptions⁴⁸ and their relationships with other farmers or stakeholders⁴⁹.

Depending on the scale, the timeframe and the definition, resilience-enhancing attributes could differ from the ones described in this study¹⁴. One could argue, from a socio-ecological perspective, that resilient farms may exhibit variable production as a strategy to cope with shocks and stresses. For example, in response to high concentrate costs, they might reduce their use, leading to lower milk production, or in a poor forage year, they could decrease herd size, which would also reduce total milk output. Faced with low profitability, farmers may even decide to change their type of production. This aspect of resilience relates to the capacity for renewal, reorganization and development⁵⁰. These dimensions are not addressed in our study, and it is undeniable that assessing socio-ecological resilience would require multidisciplinary approaches, including qualitative methods that would offer additional understanding and nuanced insights¹⁴.

Dairy farms' characteristics and resilience

Using R_p , intensive crop productions have been found to be more sensitive to climate variability¹¹; however, to our knowledge, no published study has yet applied R_p to animal production systems. Therefore, in the following section, we compare our results with other resilience estimations in the dairy sector based on alternative methodologies. Using a qualitative approach on multiple facets of resilience (social, economic, and agroecological) through interviews with farmers, a previous study also suggested that intensive dairy farms were less resilient than extensive ones²⁷. In contrast, the intensive grass-based farm type (IG) in the present study had the highest resilience of gross and net productivity. This result suggests that intensive farms may exhibit some positive traits in terms of resilience, in this specific case of the Walloon region and according to the production resilience indicator. Moreover, as IG had the highest mean net productivity and resilience of net productivity, it has the ability to combine the dimensions of food availability and stability of supply to support food security.

In contrast, IM had less resilience of net productivity than EG. As both grass-based types had the highest resilience of net productivity, feeding grass seems to be a factor that could increase resilience of the contribution to food security. The importance of grass-based feed to perceived resilience by farmers has been discussed for organic dairy farms, for which it decreased costs and increased self-sufficiency and farmer satisfaction⁵¹. In other studies, intensive grass-based dairy systems have also been shown to perform best in terms of multidimensional sustainability⁵² suggesting that such systems may also be capable of reconciling the two complementary concepts of resilience and sustainability²⁹. Nevertheless, some grasslands could be tilled and converted into direct food crop production⁵³. This aspect is not taken into account by the net productivity indicator⁶. Moreover, as the present study focused on specialised dairy farms, and system diversification has been suggested as one way to increase resilience^{51,54} it would be interesting to assess the production resilience of crop-livestock dairy farms.

After the end of milk quotas, the resilience of gross and net productivity decreased for all three types of farms, but the mean gross and net productivity decreased only for EG. Thus, EG's decrease in resilience was associated mainly with its decrease in mean productivity. In contrast, the decrease in resilience for IM and IG was due mainly to an increase in the variance of milk and meat protein production per ha. Notably, the observed increase in variance seems consistent with the effects that were predicted before milk quotas were ended²⁶. Other factors could have influenced the decrease in resilience after the end of quotas, such as climate change. For example, the Walloon region was in average drier from 2016 to 2020 than from 2011 to 2015 (mean Standardised Precipitation-Evapotranspiration Index⁵⁵ of -0.11 and -0.34, respectively⁵⁶). However, the year had relatively little influence (i.e. explaining less than 2% of the variance in gross and net productivity), which suggests that farm types responded differently to the same climate years.

It may seem counterintuitive that no clear increase in gross productivity was observed for IG and IM between the two considered periods of this study, given that statistics indicate a 18% increase in milk production per farm in Belgium from 2015 to 2020. However, these overall figures mask consequent regional disparities, with Flanders experiencing a 25% increase, while Wallonia saw only a modest 2% growth²³. Now, even with this small total increase in milk delivery, Walloon dairy farms have experienced a reduction in the number of dairy cows (-9%) and dairy farms (-17%), associated with a growth in the average milk production per cow (+12%) and per ha (+22%)^{23,57}. However, in the gross productivity indicator, imported surfaces through purchased feedstuffs are also included in the denominator, and we observe an increase in the use of concentrates during the period under consideration⁵⁸. Moreover, the farm sample used in this study consists of farms that have existed since at least 2010. If these farms had been transferred and substantial investments had been made to modernize them, they would have received a new accounting ID and would not have been included in this study.

The decrease in resilience of dairy systems after the end of quotas was associated with type-specific changes in farm characteristics. First, the two intensive types (IG and IM) became even more intensive by increasing milk production and the amount of concentrates fed per cow. However, this intensification can lead to unexpected consequences, such as occasional increases in the number of sick animals, which causes milk production to vary and thus influences the resilience of gross and net productivity⁵⁹. However, the stocking rate of IG and EG decreased, which can increase resilience because adapting the herd size to the potential production of the land available can increase flexibility⁵⁴. Furthermore, a lower stocking rate can help respond to drought⁶⁰. The CP content of concentrates decreased for IG, which can increase the resilience of net productivity because high-protein concentrates rely on a few feed ingredients that compete with human food, especially soya bean meal². Improving herd management (i.e. age at first calving and number of female followers per dairy cow) can also increase gross⁶¹ and net productivity⁶. These two characteristics decreased for IM but increased for EG. As EG became more extensive after the end of quotas, not all farms followed the predicted intensification pathway²⁶. However, these results correspond to the two contrasting dairy systems that Walloon dairy farmers described

as their “ideal future farms”⁶². Moreover, this difference in the evolution of dairy systems can help increase resilience at the regional scale⁶³.

Future threats for the resilience of the Walloon dairy sector

To ensure the future resilience of dairy farms, several key contextual factors must be addressed. Similar to other European regions, the Walloon region is experiencing a considerable decline in the number of farms⁶⁴. Although total milk production in Wallonia has remained relatively stable, the fact that it is now sustained by a decreasing number of farms may affect the resilience of the region's contribution to food security. This underlines the importance of assessing resilience at a broader scale than the individual farm, an approach that is currently underrepresented⁴⁸. R_p can offer valuable insights into the resilience of regional production, directly based on national production statistics, as demonstrated for major crop productions across various countries by Zampieri et al. (2021)⁶⁵. However, to achieve a comprehensive understanding of socio-ecological resilience at the regional scale, it would also be necessary to integrate other stakeholders, such as actors in the supply chain and in the more global rural community⁶⁶ into the assessment¹⁴.

Resilience should also be assessed over the long term, as strategies that appear beneficial in the short term may have detrimental consequences in the longer run⁶⁶. Indeed, the farming population is aging, with the average age of Walloon dairy farmers now reaching 50 years⁶⁷. Succession has become a critical issue, as the demanding workload and substantial financial investments required for dairy farming have made the profession less appealing to younger generations⁶⁸. Land accessibility further complicates the situation. Between 2017 and 2022, the price of arable land in Wallonia increased by 6.0%, while the cost of permanent grassland rose by 7.6%, creating additional barriers for aspiring farmers⁶⁹. On top of these challenges, uncertainties surrounding the Common Agricultural Policy (CAP) raise concerns about its capacity to support future generations of European dairy farmers and provide a stable framework for milk production. R_p can offer valuable insights into these future dynamics of resilience. However, as a diagnostic tool, it does not identify the underlying causes of resilience changes. In the future, it could serve as a useful monitoring tool for agricultural and livestock systems and be integrated with other data to enable a more comprehensive assessment.

Conclusion

This study demonstrates that the production resilience indicator (R_p) is a pertinent tool for quantifying the production resilience of dairy farming systems. It provides valuable insights into the resilience of food availability from dairy systems in the Walloon region, contributing to the European Commission's call for operationalizing farm resilience and could be applied on a larger scale and for other animal productions with the proposed methodology based on FADN-data. Our results highlight the importance of considering not only the gross milk and meat production in the frame of the stability dimension of food security, but also the penalizing use of human-edible feedstuffs, represented by the net productivity. Grass-based systems, particularly intensive grass-based farms (IG), demonstrated higher resilience, challenging the assumption that intensive farms are less resilient. Following the end of milk quotas, resilience decreased across all farm types, due to increased variability in productivity for the two intensive farm types, and a decrease in mean productivity for the extensive grass-based farm type (EG). These changes were associated with type-specific modifications in farm characteristics, highlighting the need to approach resilience specifically for the diversity of existing farms. The conclusions of this study are limited because only five years before and after the end of quotas were considered, and other factors could have influenced the variance in gross and net productivity after 2015, such as climate change. While the study provides a robust framework for assessing production resilience, broader multi-disciplinary approaches are necessary to capture the full scope of socio-ecological resilience. Both approaches could be simultaneously applied in future studies. Given the actual context, notably the ongoing decline in farm numbers and succession challenges, ensuring the future resilience of dairy systems remains a critical priority at both regional and European levels.

Data availability

The data that support the findings of this study are available from Walloon Department of Agricultural Economic Analysis and the Walloon Breeders Association but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the two farm accounting organisms.

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Author contributions

Conceptualisation, C.B.N. and M.Z.; Methodology, C.B.N. and M.Z.; Software, C.B.N., Investigation, C.B.N. and M.Z.; Writing – Original Draft, C.B.N.; Writing – Review & Editing, C.B.N., D.S., E.F., Y.B. and M.Z.; Supervision, Y.B., E.F., and D.S.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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