Assessment of the buffering and adaptive mechanisms underlying the economic resilience of sheep-meat farms

Marc Benoit, Frédéric Joly, Fabienne Blanc, Bertrand Dumont, Rodolphe Sabatier, Claire Mosnier

To cite this version:

Marc Benoit, Frédéric Joly, Fabienne Blanc, Bertrand Dumont, Rodolphe Sabatier, et al.. Assessment of the buffering and adaptive mechanisms underlying the economic resilience of sheep-meat farms. Agronomy for Sustainable Development, 2020, 40 (5), 10.1007/s13593-020-00638-z . hal-02925854

HAL Id: hal-02925854
https://hal.inrae.fr/hal-02925854v1

Submitted on 31 Aug 2020

Agronomy for Sustainable Development (2020) 40:34
https://doi.org/10.1007/s13593-020-00638-z

RESEARCH ARTICLE

Assessment of the buffering and adaptive mechanisms underlying the economic resilience of sheep-meat farms

Marc Benoit[1] · Frédéric Joly[1] · Fabienne Blanc[2] · Bertrand Dumont[1] · Rodolphe Sabatier[3] · Claire Mosnier[1]

Accepted: 3 August 2020

Abstract

The sustainability of livestock systems can be assessed through their productive and environmental performance, the ecosystem services they provide or their resilience to hazards. We used a modelling approach to assess how key economic performance indicators respond to technical and market hazards in five different meat-sheep farms, across France and Ireland. Hazards were related to seven technical or economic variables: ewe fertility, prolificacy, lamb mortality, prices of light and heavy lambs, concentrate use and energy use. We used a mechanistic model to simulate farm functioning and assess farm performance over 3000 iterations, based on simultaneous random draws with hazards to the previously mentioned seven variables. We quantified this way (i) the compensatory effects of different types of technical and economic mechanisms that lead to more stable economic performance and (ii) the probability of economic collapse of meat-sheep farms through a diachronic analysis. We showed that variations in technical variables have larger effects on income variability than variations in economic variables. We also showed that the most resilient systems, i.e. those with the lowest coefficient of variation of net income, are those that combine a low level of inputs with at least two lambing periods per year. Short duration of pregnancy in ewes makes multiperiod lambing possible, which can buffer the variability of technical variables and enhance the adaptive capability of the system by offering the possibility to move empty ewes to a new batch for re-mating. We thus analysed for the first time farm economic resilience to combined technical and economic hazards, and highlighted the buffer and adaptive mechanisms of resilience, with a mechanistic model.

Keywords Modelling · Hazards · Resilience · Economics

1 Introduction

Livestock farming faces many societal and environmental concerns, particularly regarding herbivore emissions of greenhouse gases, land use, and limited feed conversion efficiency. However, there is evidence that herbivore farming systems have a specific role in sustainable food systems, as herbivores (i) use grasslands and rangelands that are not cultivable and are at risk of shrub encroachment, (ii) use forages and crop residues from rotations from integrated crop-livestock systems and (iii) provide nitrogen in their manure, hence reducing the inputs needed for crop production (Van Kernebeek et al. 2016, van Zanten et al. 2016, Barbieri et al. 2019).

In a previous article (Benoit et al. 2019), we identified five different highly efficient meat-sheep farms. These farms were chosen for their high efficiency in terms of ewe productivity relative to concentrate feed use. We quantified how their contrasting management strategies led to high economic and environmental performance, including limited feed–food competition. The five farms were located in lowlands or uplands along a gradient of decreasing agronomic potential from Ireland to the French Mediterranean rangelands. The strategies pursued in these systems aimed to adapt farm management to their pedoclimatic context and to increase the use of grasslands and rangelands by matching animal feed requirements to forage availability. This often resulted in highly

---

✉ Marc Benoit
marc-p.benoit@inrae.fr

[1] Université Clermont Auvergne, INRAE, VetAgro Sup, UMR Herbivores, F-63122 Saint-Genès-Champanelle, France

[2] Université Clermont Auvergne, VetAgro Sup, INRAE, UMR Herbivores, F-63122 Saint-Genès-Champanelle, France

[3] INRAE UR 767 Ecodeveloppement, F-84000 Avignon, France

seasonal meat production and thus lesser adaptation to the meat industry and market demands. Here, our objective is to take a step forward in this analysis by modelling the resilience of these five meat-sheep farms to a range of technical and economic hazards.

Resilience is a polysemous word, but all of its meanings refer to the ability of a system to deal with uncertain events. Holling (1996) distinguishes two forms of resilience: engineering resilience, which corresponds to the time necessary to return to an equilibrium after a perturbation (Pimm 1984), and ecological resilience, which corresponds to the magnitude of a perturbation that a system can absorb before shifting to another regime of functioning (Sabatier et al. 2017). These last authors quantified ecological resilience as the proportion of stochastic climate shocks that do not affect system viability.

Resilience can result from several system properties, such as its buffer, adaptive and transformative capabilities (Darnhofer 2014). Buffer capability describes the ability of a system to absorb a perturbation without changing its structure or function. Adaptive capability denotes the ability of farmers to make decisions to adjust in the face of external drivers. The first dimension of resilience is rather passive, whereas the second is active and related to tactical farming decisions. Transformative capability implies a transition to a new system with different characteristics and structure.

Several models have also assessed the resilience of livestock farms through their ability to maintain income stability in an uncertain context (Mosnier et al. 2009, Tzouramani et al. 2011, Diakité et al. 2019). Following this last approach, we assessed economic resilience through a set of properties that reveal how systems deal with different types of uncertainties. First, we studied the distribution of farm net income in response to key market and technical hazards. We evaluated the resilience of a farm on the basis of the coefficient of variation of its net income, thus taking into account its variability as well as the security associated with a high average income level. Second, we assessed the probability of occurrence of 2–3 successive years of reduced income that could jeopardize farm activity. In line with Tzouramani et al. (2011), we assessed the resilience of sheep farms in relationship to economic drivers: meat and input prices. In addition, we accounted for the three main drivers of flock technical performance: ewe prolificacy, lambing rate and lamb mortality. At an annual scale (or “campaign” scale), the lambing rate depends on ewe fertility and breeding management. The short pregnancy period of ewes makes the acceleration of reproduction possible (lambing intervals of 8 months instead of twelve) and opens up the possibility of varied and complex reproduction rhythms such as three lambings over 2 years. We assume that ewe prolificacy, lambing rate and lamb mortality are fundamental in the variability of flock productivity because their range of variability is wide, particularly for prolificacy, which can range from 110% up to 200% or even 250% for some breeds. We can consider that some specific hazards, such as health problems, which lead to a decrease in production, are indirectly taken into account through these three technical variables. Indeed, they can strongly impact herd productivity and economic results (Perrin et al. 2011, Gethmann et al. 2015). We used a whole-farm simulation model that allows us to generate hazards and calculate their impact on economic indicators (Benoit 1998, Benoit et al. 2019) to simulate farm performance across a wide range of environmental conditions.

The objectives of this paper are thus to assess (i) income distribution and variability in each farm in the face of hazards, (ii) farm economic sustainability, determined by the probability of having successive years with given drops in income and (iii) the relative contribution of each variable that involves hazards and leads to income variability, in order to identify the internal mechanisms underlying sheep farm economic resilience.

2 Material and methods

2.1 Farm selection

The reasons behind the selection of these five systems are detailed in Benoit et al. (2019) but can be summarized as follows. These farms are located in various pedoclimatic contexts and present diverse reproduction management strategies: one lambing period (end of winter), two lambing periods (end of winter and autumn) and three lambing periods (April, September, December) with lambing acceleration. The first farm is in Ireland, and the last four are in France. Irel is a one-lambing system in humid oceanic conditions. Graz (grazing farm) is a system based on two unbalanced lambing periods per year in the French western lowlands. 3 × 2, in the French Massif Central uplands, is an accelerated reproduction system with three lambings every 2 years and three lambing periods (Fig. 1). OF (organic farming) is a balanced lambing period system of the Massif Central uplands following the organic system specifications, aiming for a high forage autonomy. DT (very mobile, dual transhumant) is a Mediterranean system mainly relying on rangelands for forage resources. These farms were selected from a database of 118 farms and were among those in which the lowest amount of concentrate feed (kg of concentrate for the flock, per breeding ewe and per year) was used for a given ewe productivity level (i.e. percentage of lambs produced per ewe per year). Ewe productivity levels ranged from 82 to 166% and concentrate consumption from 0 to 134.6 kg ewe^{-1} for the *DT* and *3 × 2* farms, respectively. Their functioning and performance were calculated based on 3- to 5-year averages, and the economic data were generated based on the 2015 economic context (main features of the farms are described in Table 1). To sum up, we studied five contrasted farming systems that are representative of the

Fig. 1 The local Rava breed, in the French Auvergne region, is well adapted to the mountain area context and resources and can be managed in a three lambings in a 2-year breeding system, which provides stability in annual ewe productivity (Pictures M. Benoit)

diversity of local meat sheep farming systems but with remarkably high economic performance, in terms of income. We assume that this contrast enhances the value of our research.

2.2 Selection of variables subjected to hazards

Seven variables were selected to be subjected to hazards because of their importance to farm technical and economic

Table 1 Main characteristics of the five farms: 1/structure, flock size, 2/technical performances, types of lambs produced and their characteristics, concentrate use, 3/net income and its standard deviation when farms are submitted to hazards on technical variables (fertility, prolificacy, lamb mortality) and on economic variables (prices on lambs, concentrates, fuel, N-fertilizer, powdered milk), 4/level of subsidies. Irel for the Irish system, Graz for grazing, 3 × 2 for accelerated reproduction system, OF for organic farming, and DT for dual transhumant system. Yearly data

Farms	Irel	Graz	3 × 2	OF	DT
Structure					
Total agricultural area (ha)	36.8	81.9	53.9	91.9	4463
Stocking rate (ewe/ha fodder area)	11.4	6.6	8.7	4.4	0.5
No ewe (> 6 months)	420	541	470	405	2105
Total workers (UWH)	1.00	1.50	1.50	1.00	4.67
Family workers (UWH)	1.00	1.00	1.50	1.00	3.00
Flock management, feeding, production performance and lambs characteristics					
Prolificacy (%)	218	155	166	174	109
Ewe fertility (%)	95	85	82	92	90
Lambing rate (%)	86	94	121	88	86
Lamb mortality (%)	18	9	17	14	12
Ewe productivity (+6mths) (%)	154	133	166	132	82
Production (kg carc ewe^{-1})	29.9	27.2	25.7	22.6	10.0
Fattened (“heavy”) lambs (%)	100.0	100.0	89.4	100.0	70.4
Weight of fattened lambs (kg carc)	19.9	20.0	16.3	17.0	16.6
Price of fattened lambs (€.kg carc^{-1})	4.76	6.43	6.64	7.03	7.82
“Light” lambs (%)	0.0	0.0	10.6 (1)	0.0	29.6 (2)
Price of light lambs (€ head^{-1})	–	–	84.0	–	65.0
Concentrates (kg ewe + 6 months^{-1})	36.5	42.2	134.6	77.1	0.0
Economic performance					
Net Income (€ FW^{-1})	6238	36,710	25,571	41,864	60,061
Net income standard deviation (€ W^{-1}) (hazards on 3 technical and 4 economic variables)	6947	4612	3650	4378	4733
Total subsidies (€.FW^{-1})	13,401	28,376	27,565	55,396	61,365

To be slaughtered; 25 kg LW; specific market

To be fattened; sold at weaning (females) performance. In the French context, the economic performance of farms is essentially dependent on ewe productivity and concentrate consumption (Benoit and Laignel, 2011, Bellet and Ferrand, 2014). We have thus used Eq. [1] to calculate ewe productivity (on a yearly basis) from the three following components: (i) the lambing rate, which is the number of lambings per ewe and per year; (ii) annual flock prolificacy (number of lambs born divided by the number of lambings) and (iii) annual lamb mortality.

The lambing rate results from ewe fertility and reproduction strategies. This includes the possible acceleration of the lambing rhythm (8 months between lambing intervals instead of 12 months) as well as the possibility of moving empty ewes from a breeding batch to the next one and remating them early. As these activities result from farmer decisions, we can consider them part of an internal "adaptive mechanism".

$$\text{Ewe productivity} = [\text{Lambing rate}] \times [\text{Prolificacy}] \times [1-(\text{Mortality rate})] \tag{1}$$

We also selected four key economic variables related to meat production and input prices: (i) the selling prices of heavy and (ii) light lambs that have to be considered separately due to different markets, (iii) the concentrate price, which represents the main sheep production cost (Benoit and Laignel, 2011) and (iv) the oil price, for the estimation of energy costs that can fluctuate dramatically and impact not only the price of fuels but also the price of synthetic nitrogen (fertilizer) and powdered milk for lambs. Regression equations [a–d] established from French statistical data (AGRESTE, data from 1998 to 2007) were applied to link the prices of these three key farm inputs (fuel and diesel, nitrogen fertilizer and powdered milk) to oil prices.

[a] Price of fuel oil (€/l) = $(P_f \times 0.7633 + 14.027)/100$ with $r^2 = 0.97$
[b] Price of diesel (€/l) = $(P_f \times 0.9528 + 41.842)/100$ with $r^2 = 0.98$
[c] Price of nitrogen fertilizer (€/kg) = $(P_f \times 0.5722 + 45.62)/100$ with $r^2 = 0.72$
[d] Price of powdered milk (€/kg) = $(P_f \times 0.8867 + 104.37)/100$ with $r^2 = 0.68$

where P_f is the price of a barrel of fuel (€/barrel).

2.3 Model description and iteration implementation

The numerical simulations relied on the Ostral model (Benoit et al. 2019), which is a mechanistic model of flock and farm operation management. Ostral was designed to simulate flock functioning in terms of reproduction and to calculate flock performance indicators such as ewe productivity (Benoit 1998). It accounts for the various reproduction strategies that occur in sheep-meat production systems and the use of different types of resources (various fodder types, crops used as concentrate feed and cash crops). Ostral provides accurate data about the amount of meat produced and inputs needed (both operational and structural costs).

The net income was defined as the gross product (meat and wool, subsidies), minus operational and fixed costs, depreciation, financial costs, taxes, wages and social contributions. A change in fertility, prolificacy or mortality levels results in a change in the number of lambs produced and the associated costs, which are calculated at a yearly scale.

Three thousand combinations of values for the seven selected hazard variables were randomly drawn, assuming independence among the different hazards. The order of these 3000 draws was maintained for the five farms in order to carefully compare the temporal succession of hazards over years (see 3.4). The number of iterations was chosen so that the income standard deviation would no longer be sensitive to an increase in the number of iterations. Ostral does not maintain any intermediate values between its two successive iterations, which means there is no cumulative effect across 2 years. Each year (or iteration) is built on the same farm baseline in terms of flock lambing organization.

2.4 Simulation of hazards

2.4.1 Variability of parameters for random draws

The hazards for each variable are considered to follow a normal distribution based on an average value and a standard deviation, which can be supposed to vary or not by farm. For the economic variables, the average values of the seven stochastic variables are specific to each farm, and the standard deviations between farms are set as identical. This was decided in order to reflect the fact that market prices are exogenous data that vary due to global market changes. The SDs were chosen based on expertise and data from a 30-year survey of a total of 118 sheep farms (Benoit and Laignel, 2011, Benoit et al. 2019). The standard deviations used were 0.2, 0.04 and 10 for the variables sheep meat price (€ kg carc^{-1}), concentrate price (€ kg^{-1}) and oil barrel price (€ Baril^{-1}), respectively.

The technical variables are considered to be independent, which is not totally true, as they can be connected in some situations. However, the relationship is not systematic (i.e. it depends on various causes), and correlation parameters are not available. For example, energy deficiency in the diet can affect both fertility and prolificacy. However, sanitary problems such as bluetongue can affect fertility and lamb mortality but not prolificacy.

Table 2 Description of 13 random draws corresponding to seven variables and three possible lambing seasons per year. Standard deviations chosen for each variable and farming system. SD = standard deviation and CV = coefficient of variation. Irel for the Irish system, Graz for grazing, 3 × 2 for accelerated reproduction system, OF for organic farming, and DT for dual transhumant system

Variables		Period	Random draw value	SD or CV	SD for random draws				
					Irel	Graz	3 × 2	OF	DT
Technical variables	Fertility rate (%)	Spring	V 1	SD	5.0	5.0	5.0	5.0	5.0
		Autumn	V 2			5.0	5.0	5.0	5.0
		Winter	V 3				5.0		
	Prolificacy rate (%)	Spring	V 4	CV (0.06)	13.2	9.5	10.1	10.6	6.6
		Autumn	V 5			9.5	10.1	10.6	6.6
		Winter	V 6				10.1		
	Mortality rate (%)	Spring	V 7	CV (0.5)	9.0	4.6	8.5	7.0	6.0
		Autumn	V 8			4.6	8.5	7.0	6.0
		Winter	V 9				8.5		
Prices	Heavy lambs (€/kg)	Year	V 10	SD	0.2	0.2	0.2	0.2	0.2
	Light lambs (€/kg)	Year	V 11	SD	0.2	0.2	0.2	0.2	0.2
	Concentrate (€/kg)	Year	V 12	SD	0.04	0.04	0.04	0.04	0.04
	Energy (€/barrel)	Year	V 13	SD	10.0	10.0	10.0	10.0	10.0
	Fuel and diesel	Year		Calculated from energy price with regression equation					
	Fertilizat. N	Year							
	Powdered milk	Year							

We used the same standard deviation between farms for the fertility variable (5%) (Table 2) because ewe fertility rates vary on a small range between farms and seasons (from 80 to 96% for multiparous ewes). For the variables lamb mortality and prolificacy, the ranges are very large between farms and seasons. For example, prolificacy for spring lambing is 220% for Irel and 112% for DT; lamb mortality is 18.5% for 3 × 2 spring lambing and 8% for Graz autumn lambing. It was not appropriate to use the same standard deviation in such different situations; therefore, we established a common coefficient of variation between farms for these two variables, i.e. 0.50 for mortality and 0.06 for prolificacy. These values led to standard deviations consistent with the variations observed on farms through long-term farm monitoring (Benoit and Laignel 2011).

It is noteworthy that the hazards for each of the three technical variables were considered separately according to the three possible lambing periods (spring, autumn and winter) that can occur in each farm. Each technical variable was thus randomly drawn in each lambing period using similar variation coefficients (Table 2).

2.4.2 Decomposition of the observed overall variability

To understand the effects of hazards on farm income, we considered their effect on five economic indicators: lamb sales, concentrate cost, nitrogen fertilization cost, fuel cost and powdered milk cost. Sales and cost variations result from changes in both quantity and unit price. The fertility rate, prolificacy rate and mortality rate impact lamb production as well as the quantity of concentrate feed and milk powder consumed and marginally affect fertilization and fuel quantities, depending on forage needs. To disentangle the price and quantity effects of the seven random variables (fertility rate, prolificacy rate, mortality rate, heavy lambs price, light lambs price, concentrate price, energy price), we analytically isolated the effects due to prices and quantities through Eq. (2) and Eq. (3).

$$\Delta P_{\mathrm{i,n}} = \left(p_{\mathrm{i,n}} - p_{\mathrm{i,0}}\right) \times k_{\mathrm{i,0}} \tag{2}$$

$$\Delta K_{\mathrm{i,n}} = \left(k_{\mathrm{i,n}} - k_{\mathrm{i0}}\right) \times \mathrm{p}_{\mathrm{i,0}} \tag{3}$$

where $\Delta P_{\mathrm{i,n}}$ and $\Delta K_{\mathrm{i,n}}$ are, for economic indicator i (lamb sales and concentrate, N fertilization, fuel and powdered milk costs) and iteration n, the differences in farm income from the baseline scenario due to price variation ($\Delta P_{\mathrm{i,n}}$) and quantity variation ($\Delta K_{\mathrm{i,n}}$). $p_{\mathrm{i,n}}$ is the price of variable i and $k_{\mathrm{i,n}}$ is the quantity of variable i as provided by Ostral. $p_{\mathrm{i,0}}$ is the baseline price, and $k_{\mathrm{i,0}}$ is the baseline quantity. ($k_{\mathrm{i,n}}$–$k_{\mathrm{i,0}}$) values depend directly (number of lamb produced) or indirectly (for other functional variables depending on the number of lambs produced) on fertility, prolificacy and lamb mortality variations. The standard deviations of $\Delta P_{\mathrm{i,n}}$ and $\Delta K_{\mathrm{i,n}}$ on the 3000 iterations were then calculated and compared with the income standard deviation.

To further elucidate the role of ewe productivity in the income SD, we disentangled the effects of the three components of ewe productivity subjected to hazards following the same approach (V1 to V9, Table 2). We considered, for example, $\Delta EP_{Prolif,n}$, the variation in ewe productivity as a result of the yearly variation in prolificacy for iteration *n*, if hazards V4 to V6 were applied to prolificacy with no hazards to ewe fertility or lamb mortality (Eq. 4). We did the same for $\Delta EP_{LambR,n}$ (with "LambR" as lambing rate; Eq. 5) and $\Delta EP_{1\text{-}Mort,n}$ (with "Mort" as lamb mortality; Eq. 6)

$$\Delta EP_{Prolif,n} = (Prolif_n - Prolif_0) \times Fertil_0 \times (1 - mort_0) \quad (4)$$

$$\Delta EP_{LambR,n} = Prolif_0 \times (LambR_n - LambR_0) \times (1 - mort_0) \quad (5)$$

$$\Delta EP_{1-Mort,n} = Prolif_0 \times LambR_0 \times (mort_0 - mort_n) \quad (6)$$

For each of those three variables ΔEP, as the hazards on the three technical variables are different between the three possible lambing periods, Ostral provided a yearly average weighed by the number of lambings (for fertility) or lambs born (for prolificacy and mortality) during each lambing period.

The lambing rate depends on two factors: ewe fertility and farmer decision for managing the batches of ewes for reproduction. To clarify the relationship between fertility and lambing rate, we disentangled the lambing rate variation (Eq. 7) into (i) the flock fertility for each of the three possible lambing periods, (ii) the "buffer effect" of disconnected fertility hazards between lambing periods (passive mechanism of dilution of risks between seasons) and (iii) the "adaptive effect" resulting from farmer decisions to move empty ewes from one breeding flock to the next breeding flock to remate them quickly and to accelerate reproduction or not (active compensation mechanism).

$$\sigma\, LR = \sigma\, Fert_{1,2,3} - \sigma\, Fert_{buff} - \sigma\, FS_{adapt} \quad (7)$$

where σ LR is the SD of the lambing rate for 3000 iterations, $\sigma\, Fert_{1,2,3}$ is the average SD of ewe fertility for the three lambing periods (weighted by the number of lambings in each period), $-\sigma\, Fert_{buff}$ is the reduction in the SD of yearly fertility linked to disconnected hazards to the fertility rate between mating seasons, and $-\sigma\, FS_{adapt}$ is the reduction in the SD of yearly fertility linked to the stabilization of the lambing rate related to farmer breeding strategies.

2.5 Indicators selected to analyse economic resilience

The contribution of each studied factor (fertility, prolificacy, lamb mortality, prices of lambs, concentrate, fuel, fertilisers, powdered milk) to the overall change in net income can be studied on the basis of either net income per worker or net income per ewe. We selected the latter to easily highlight the consequences of the farmers' management strategies at the animal level. This choice does not modify the contribution of each variable to the global SD (of net income) for a case study, as there is a linear relation between these two indicators based on the number of ewes per worker (constant values for each farm).

Income variability is only one aspect of resilience and has to be combined with the level of income itself. Indeed, a high level of income can ensure a strong economic resilience, despite some variability. Thus, the income coefficient of variation will be used in the section comparing farm economic resilience.

2.6 Analysing the effect of hazards occurring in successive years on farm sustainability

After assessing the global effects of different hazards on farm income, a second step of this study consisted of assessing their impacts over successive years. Successive hazards can jeopardize farm activity, indicating the limit of the adaptive capability of the farm and thus lower resilience. We thus analysed the evolution of the net income of the five farms under the same 3000 stochastic simulations. In doing so, we aimed to identify the occurrence of two or three successive years with a drop in income (or with a percentage of drop in income) as a result of combined unfavourable hazards to the seven variables previously described, and the possible bankruptcy of the farm. Two metrics were considered:

- The frequency of several (two or three) successive years with a level of drop in income (or percentage of drop in income) over a given value, compared with the reference income (average level)
- The frequency of three successive years during which the average drop in income (or the average percentage of drop in income) exceeds a given value, which we varied to simulate different levels of financial difficulty. This metric introduces compensatory effects between years, particularly if the 3 years study includes one very good year combined with two hard years.

The first metric is well adapted to take into account the succession of two difficult years resulting from very unfavourable timing of hazards. The second one is more adapted to assess the impact of a combination of hazards with smaller impacts that repeat over successive years (Mosnier 2015).

3 Results and discussion

3.1 Analysis of the income variability

The Irish system (Irel) had the lowest average net income, at 6238 € per worker. It suffered from an adverse economic context for lamb prices, public support and land prices; all three of which were unfavourable compared to French conditions. Moreover, Irel presented the highest standard deviation (SD), at 6947 €, which can be explained mostly by the single lambing period, which does not allow compensating for any decrease in ewe fertility and does not allow any buffer effect. Conversely, the income distribution is less variable in the accelerated reproduction system (3 × 2) based on three lambing periods, with a 3650 € SD and 25,571 € income per worker. The net income SDs are intermediate for DT, Graz and OF systems, at 4733 €, 4612 € and 4378 €, respectively, with higher net incomes compared to Irel and 3 × 2, at 60,061 €, 36,710 € and 41,864 €, respectively. The highest level of income, observed in *DT*, is related to its very low dependency on inputs and high labour productivity (Table 1).

3.2 Breakdown of quantity and price effects

Figure 2 shows that the net income variability (global SD) is lower than the sum of the SDs of the factors studied due to the independence of the hazards applied to the seven variables studied (Table 2).

We first observed the key impact of ewe productivity (see Fig. 2, gross product (technical hazards)), which includes fertility, prolificacy and lamb mortality effects. Its SD represents 48% to 76% of the total SDs (of gross product and cost of inputs). The second most important SD is related to the variation in the price of meat (gross product (economic hazard)), which represents between 18% and 22% of the total sum of SDs. A notable exception is the 3 × 2 system in which the impact of concentrate price comes in second place, representing 21% of the sum of SDs (vs 19% for variations in meat price). The sum of the SDs for the other variables (fertilization, powdered milk and energy, both on prices and quantitative impact) represents between 5.1 and 10.1% of the sum of the SDs by farm. Among these variables, fertilizers (the sum of the effects of price and quantity) represent 3.4% of the SDs for Irel, powdered milk represents 4.6% of the SDs for Irel, and fuel represents 7.3%, 6.1% and 6.0% of the SDs for OF, DT and 3 × 2, respectively. All other variables have lower contributions to the SDs.

As DT does not use concentrates and uses very little fertilizer and fuel, the SD linked to gross product (technical hazards) represent the main part of the sum of SDs on this farm, i.e. 76% vs. 58% on average for the four other farms.

The economic SD expressed by ewe (Fig. 2) allows a study of the economic impact of the seven variables on the net income components they impact and the compensation effects. DT is the most stable system when looking at net income SD per ewe. However, at the farm level, looking at net income SD per family worker, 3 × 2 is the most stable system, due to its lower work productivity (313 ewes per family worker vs 361, 405, 420 and 842 for Graz, OF, Irel and DT, respectively). This conclusion confirms the usefulness of combining several indicators to assess farm resilience (Martin et al. 2017).

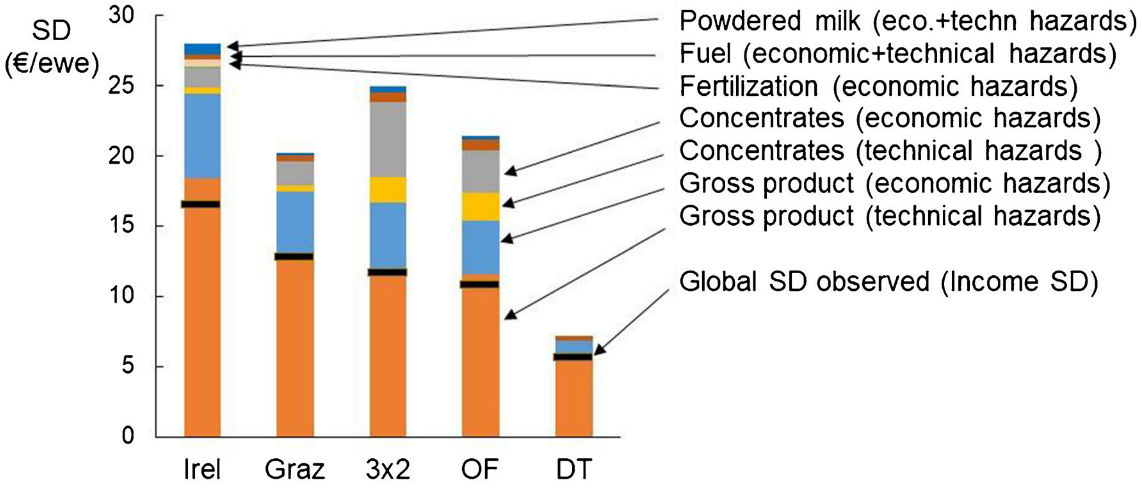

Fig. 2 Economic SDs per ewe: the overall SD for net income and the SDs of net income components affected by hazards: Gross product, corresponding to the meat produced, and costs associated to concentrate, fertilization, fuel and powdered milk use. Each component is affected by the two type of hazards considered: technical ones (in relation with ewe fertility, prolificacy, lamb mortality; see Eq. 1) and economic ones (variation in price of meat and four input considered). Irel for the Irish system, Graz for grazing, 3 × 2 for accelerated reproduction system, OF for organic farming, and DT for dual transhumant system

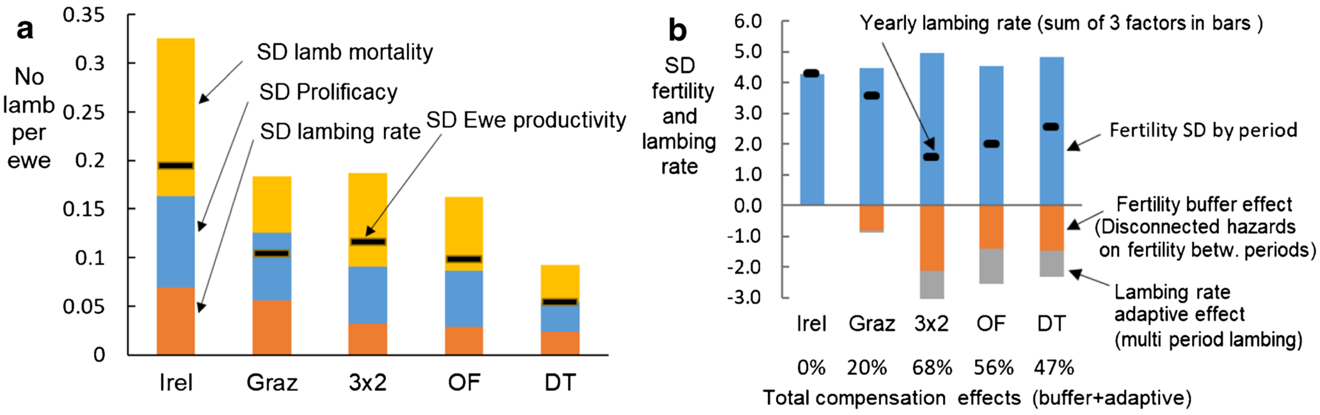

Fig. 3 **a** Standard deviation (SD) of ewe productivity, with the SDs of the 3 variables it comprises (lambing rate, prolificacy and lamb mortality). SD is expressed as the number of lambs produced per ewe per year. **b** SD of the yearly lambing rate as a result of (i) the average SD fertility rate between periods (one to three according to the farm), (ii) the disconnected hazards to fertility rate between lambing periods (buffer effect) and (iii) the possibility of a second mating for empty ewes in the next lambing period (adaptive effect). The variables yearly fertility and lambing rate are centred around the same mean for this analysis. Irel for the Irish system, Graz for grazing, 3 × 2 for accelerated reproduction system, OF for organic farming and DT for dual transhumant system

3.3 Breakdown of technical variables for analysing ewe productivity

Since the variation in the number of lambs appears to be decisive in the sum of economic SDs, we first investigated the respective and sometimes compensatory effects of the three technical variables (lambing rate, prolificacy, lamb mortality) driving both the variability in ewe productivity (Fig. 3) and SD of gross product per ewe (gross product (technical hazards) on Fig. 2).

The assumed independence of fertility, prolificacy and lamb mortality explains why the SD of ewe productivity is lower than the sum of the SD of the three variables from which it is derived (Fig. 3). The SD of lamb mortality is, on average, the most important component (44%) of the sum of three SDs, followed by prolificacy (34%) and lambing rate (22%). Lambing rate has a lower impact because fertility, which is the first component of the lambing rate, is capped at 100% in random sampling, and because low fertility levels during a given mating session can be compensated for at the next mating session for empty ewes in systems with two or three lambing periods in the year (see Fig. 3b).

The share of the SD of each of these three variables in the sum of the three SD varies significantly between farms (Fig. 3a): the lambing rate share of the SDs is the highest in Graz (30% of the sum of the SDs) and only 17% in 3 × 2. The mortality share of the SDs is also rather variable between farms and is the highest in 3 × 2 at 50%, while it is only at 32% for Graz. The prolificacy share of the SDs is rather stable among farms, ranging between 31% (3 × 2) and 38% (Graz).

The mortality SD is the highest when prolificacy baseline level is the highest (Irel, then 3 × 2), which is quite logical because of the “multiplier” effect of prolificacy on the number of dead lambs and because we integrated an increasing rate mortality in Ostral from single to twin and triplet lambs (Benoit 1998). The SD lambing rate, at the campaign scale, is the result of complex interactions and compensations. It is the combination of (i) the SD of the fertility rate in each lambing period, and thus, the 1-year average SD fertility rate in the three possible lambing periods, (ii) the mechanism of dilution effects (or “buffer effects”) for each random draw on fertility rates between lambing periods (according to the hypothesis of independence of hazards for this parameter, between periods), and (iii) the possibility, for some farming systems, to transfer empty ewes for the next mating session with a strong compensation effect on the lambing rate at the campaign scale (adaptive effect). Compensation effects (ii) and (iii) on the fertility SD at the campaign scale led to reductions of 68%, 56% and 47% in the SD of the lambing rate, respectively, for 3 × 2, OF and DT (Fig. 3b), in reference to the only effect of hazards on ewe fertility (called effect (i) above). Obviously, there was no compensation effect for Irel, with only one lambing period per year. For Graz, with a second very short lambing period in autumn, the adaptive effect is almost nonexistent.

3.4 The economic fragility of farms studied via the frequency of consecutive difficult years

The system most exposed to successive years of drop in income is Irel, for which 10% of the years (in the series of 3000 iterations) showed a drop in income over 3700 € for two successive years (Fig. 4a); Irel is also the most exposed if we consider three successive years of income decline (probability of 3%) (Fig. 4a), which can lead to the cessation of farm activity given the already low income of the farm. On the other hand, 3 × 2 appears to have the most stable income, with only

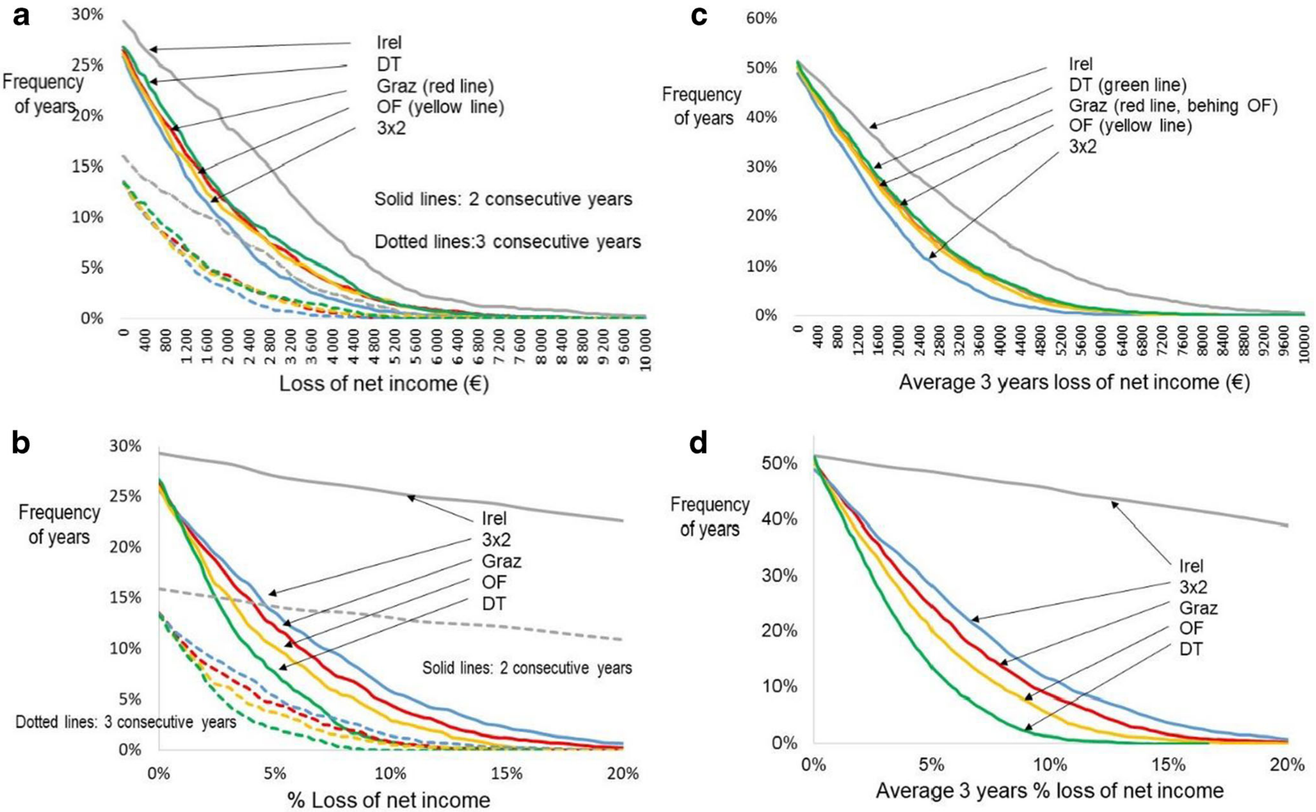

Fig. 4 **a** Frequency of two consecutive years (solid line) or three consecutive years (dotted line) with a level of drop in income over a given value (from 0 to 10,000€) and **b** frequency of two consecutive years (solid line) or three consecutive years (dotted line) with a percentage drop in income over a given value (from 0 to 20%). **c** Frequency of three consecutive years in which average drop in income exceeds a given value (0 to 10,000€). **d** Frequency of three consecutive years with an average percentage of drop in income exceeding a given value (0 to 20%). Statistics based on 3000 iterations on identical hazards (level and order) for the five farms. Irel for the Irish system, Graz for grazing, 3 × 2 for accelerated reproduction system, OF for organic farming, and DT for dual transhumant system

a 3% probability that a drop in income over 3700 € occurs over two successive years, and has an almost null probability of experiencing three successive years with this level of drop in income. The three other systems have comparable intermediate sensitivities. However, to address the notion of economic resilience, we have related the level of drop in income to its absolute level, based on the previous two metrics. Figure 4b thus shows that the hierarchy of farms is different, with an inversion of position between 3 × 2 and DT. The latter appears to be the most resilient farm, and 3 × 2 the second to last one.

The order of sensitivity to hazards of the five systems was the same when considering a 3-year average drop in income (metric 2, Fig. 4c) rather than a 2-year consecutive drop in income (metric 1, Fig. 4a). However, given the same threshold of drop in income (3700 €), the probability of occurrence of such a level of income is much higher on metric 2 compared with metric 1 (Fig. 4 a and c); this means that in metric 2, 2 years of very low income can hardly be offset by a year of higher-than-average income. Thus, there is a 17.7% probability that Irel will experience a succession of 3 years with an average drop in income higher than 3700 € (metric 2), compared with a probability of 10% for two successive years with each a drop in income higher than 3700 € (metric 1). These rates drop to 4.3% and 3% for 3 × 2 for metric 2 and metric 1, respectively, considering the same threshold of 3700 €.

Studying resilience in terms of the percentage decline in income, Fig. 4d, build according to metric 2, shows exactly the same hierarchy of farms as metric 1 presented in Fig. 4b, with, in descending order of economic resilience: DT, OF, Graz, 3 × 2 and Irel.

3.5 Comparison of the five farming systems

The results show that the 3 × 2 system has the lowest probability of successive years with a given level of drop in income and the lowest income SD. This may seem surprising considering that the 3 × 2 system heavily relies on external inputs, particularly concentrate feeds. This use of input has however a stabilizing effect in terms of income SD as price situations (meat and concentrates) are independent of each other. But more significantly, 3 × 2 was the least affected by the hazards related to reproduction performance that had the highest impact on income variability. As technical hazards for a given reproduction variable are considered independent, 3 × 2 has the strongest advantages with (i) three lambing periods that allow compensation at the year scale for factors that degrade ewe productivity and (ii) the systematic re-mating of empty ewes in the subsequent mating period, which ensures a high stability of the lambing rate indicator (Benoit 1998). In addition, the low work productivity (46 LU W^{-1}) in this system reduces the impact of income variability per ewe at the farm level. This system was however the most affected by hazards that affect the price of inputs (SD of 5.3 € ewe^{-1}, Fig. 2). Furthermore, the high level of inputs has a very negative impact on the average level of income and that penalize the farm economic resilience.

In contrast, Irel is the most sensitive to technical hazards: a single lambing period does not allow any compensation at the annual scale for ewes that are empty at the end of the mating session; the level of prolificacy is very high and therefore subject to strong variations, as is the level of lamb mortality (random sampling based on an identical coefficient of variation between farms, therefore a high SD for Irel for these two variables). In addition, the lambs were sold heavier than the lambs in the 3 × 2 system (19.9-kg vs 16.3-kg carcass), which leads to a higher production of meat per ewe (29.9 kg vs 25.7 carc ewe^{-1} for 3 × 2) despite a lower numerical productivity (154 vs 166 for 3 × 2). Hazards for the selling price of lambs then lead to higher impacts on the meat gross product, even considering the same SD for meat price in all systems. In addition, the rather high work productivity of this system (66 LU W¯1) results in the highest SD both per ewe (28 €) and per worker (6947 €).

Given the highest family work productivity of DT (122 LU W^{-1}), the income per family worker SD of this farm reaches 4733 €. Thanks to its excellent income level, the net income coefficient of variation (CV) is the lowest, at 0.079 vs 0.105, 0.126 and 0.143 for OF, Graz and 3 × 2, respectively. As it is highly penalized by a much lower sheep meat price and lower subsidies that limit its income (6238 € on average), Irel's CV reaches 1.11. The approach developed on the succession of years with a given percentage of drop in income (Fig. 4 b and d) leads to a consistent analyse with the approach based on the level of net income per worker CV.

Ultimately, among the five farming systems, DT is the one that rely less on inputs, showing both high income and rather low sensitivity to hazards. Based on the CV of the net income per worker, it would have the highest resilience. This systems reveal interesting tradeoffs between different types of performance, with high environmental performance and very low feed-food competition levels, as presented by Benoit et al. (2019), counterbalanced by specific type of lamb produced that does not fit the expectations of the meat industry. Farms OF and Graz came in second and third position in terms of economic resilience. Indeed, on the one hand these two systems are based on two lambing periods allowing compensation of technical hazards with buffer and adaptive effects, and on the other hand, they show a good level of income based on a good ewe productivity and a low use of inputs (lambs are fattened all or part of the time on grass). Then came 3 × 2 with a low economic resilience due to high input and rather low income and despite low income variability. In the last position, Irel is doubly penalised: by a single lambing period, which does not provide buffer or adaptive effect, and by a low meat price, which penalises the income.

Our results based on the SD of different variables helped to assess some mechanisms of the resilience of sheep farming systems. We showed that having several lambing periods reduces the SD of the lambing rate. This decrease, based on σ $Fert_{buff}$ and σ FS_{adapt} (Eq. 7), illustrates how the fertility risk can be diluted amongst successive lambing periods due to buffer and adaptive mechanisms. We have been able to quantify these mechanisms; all farms benefit from them except Irel, which only has one lambing period. We showed that remating (a second mating period), when accessible to all categories of reproductive females, including ewe-lambs, provides a reduction in the lambing rate SD. The OF, 3 × 2 and DT systems benefit significantly from this adaptive mechanism, which has great benefits for farm resilience.

Having several mating periods enhances the number of batches of ewes with a diversity of physiological stages, which provides opportunities for reproduction management. In this respect, our results support the agroecological principle that diversity benefits farm resilience (Dumont et al. 2013). They also support the hypothesis that diversity in reproduction channels improves buffering capacity by offering functional redundancy mechanisms (Urruty et al. 2016). Interestingly, our results show that such a mechanism is fully operational in systems with a high reliance on concentrates (for instance, 3 × 2). Such a high reliance on external inputs is not in line with agroecological principles. Thus, assessing whether a farm operates in agreement with agroecological principles would require a multicriteria evaluation of farming practices (Botreau et al. 2014) rather than only considering some technical adjustments to the system.

3.6 Sensitivity to other hazards and opportunities offered by public policies

So far, the hazards concerning the technical variables studied were considered as independent. Such work could be continued with a statistical approach related to the frequency of hazards based on local factors and the possible covariance between them. The current analysis only took into account two types of hazards related to flock technical performance and the economic context, while other hazards can affect livestock farms, particularly those associated with climate

(Blauhut et al. 2015, Belhadj et al., 2019) or farm's workforce (accidents at work, illness, etc. (Cordier et al. 2008)). It is likely that the resilience of the five systems would differ regarding the type of hazard considered (Carpenter et al. 2014) so that addressing the resilience to climate and workforce hazard remains of high interest. To analyse the effects of climatic hazards, an option would be to work with long time series on a wide range of farms (Mosnier et al. 2014) or to simulate climate hazard scenarios based on past weather series data (Joly et al. 2018). It would be particularly interesting to try identifying possible relationships between the three technical variables that drive income SD in this study, as these could be affected by climatic hazards through a change in the types and growth patterns of feed resources. It is also likely that this would in turn influence the compensation mechanisms identified in the current study.

The Irish system would be less affected by summer droughts that strongly reduce herbage yields in grassland-based systems. The DT system has a certain capacity to adapt thanks to its very low stocking rate, high diversity of resources, including shrubs and trees and altitudinal gradient of grazing areas. The Graz system is likely to be affected by climatic hazards because of the fattening of lambs at pasture in an area experiencing summer droughts. However, the use of temporary grasslands in this farming system aims to reduce the impact of such hazards by ensuring good phytomass productivity with a significant proportion of legumes in the fodder system. In 3 × 2, lamb fattening with purchased concentrates reduces the system susceptibility to climatic hazards. However, the stocking rate is high, and maintaining high reproductive performance requires particular attention to meet the ewe feeding requirements, otherwise their performance will drop. The OF system is sensitive to drought episodes as (i) synthetic fertilizers are not allowed, which limits options for securing fodder stocks, (ii) a significant proportion of the lambs are fattened on grass and (iii) the price of organic concentrates is very high.

Sheep breeding generally leads to high workload and requires a high technicality. As such, 3 × 2 that has multiple technical phases to manage during the year (mating, lambing and weaning) can appear vulnerable as inadequate work on the flock could lead to a rapid drop in technical and economic performances. Moreover, in France, sheep production is widespread, often at a low density, so that finding a worker with good technical skills to replace a sheep farmer could be more difficult than in Ireland, where sheep production remains important.

Public subsidies account for a large share of farm income. They are generally stable from 1 year to another, which strengthens farm resilience. However, in the medium and long term, they could be more oriented towards the payment of agrienvironmental services provided by the farms. DT is well positioned in this perspective, as it preserves areas with a high biodiversity potential and keeps them open to prevent running fires. There have already been proposals to quantify and pay for environmental services in the organic farming sector. Graz plays a very important role in using grasslands that contribute to carbon sequestration, water quality and water flow regulation, in areas where intensive cropping systems have negative impacts on water, landscape and biodiversity. The same opportunities exist for Irel, based on pasture use. System 3 × 2, although based on permanent pastures with a high carbon sequestration potential, may benefit less from agrienvironmental payments if subsidies were paid per hectare, as the eligible area would be rather small. Moreover, this system is the least efficient from the feed-food competition point of view, a concept that may appear in the next CAPs (Common Agriculture Policy). Thus, it appears that an orientation of the CAP towards agrienvironmental measures would further favour the resilience (in terms of income level and its CV) of the systems DT, OF and Graz, already highlighted in this study.

4 Conclusion

Modelling makes it possible to assess the relative contributions of key drivers of the variability in sheep farm performance. The risks affecting reproduction success and flock technical productivity were shown to have a greater effect than the economic variables on input and output prices. This could be explained by some key characteristics of sheep species, which has very high potential prolificacy, highly variable lamb mortality and a short pregnancy period. The latter provides the possibility to implement multiperiod lambing which can buffer the variability in technical performance and enhance the adaptive capability of the system for instance by moving empty ewes to a new batch and remating them.

The system with the least variability in income per worker is the most intensified system from a production point of view (three lambings per ewe in 2 years). Two mechanisms govern this result: (i) the disconnection between sheep meat and concentrate prices, with a high concentrate consumption and (ii) the very strong compensation for risks related to the diversification in flock organization, with the three lambing periods providing strong buffer and adaptive capabilities to the system. However, the high production costs (concentrates) resulting from this accelerated reproduction management limit income. Thus, even if the net income variations are small, the income level remains low, which increases the net income CV and therefore decreases farm resilience. In contrast, and despite its low ewe productivity, the DT system could claim the highest economic resilience thanks to its very low level of inputs and two lambing periods a year.

Ultimately, we can thus specify the two conditions under which good economic and environmental performance is associated with a high economic resilience of sheep-meat farms: (i) a reproduction system based on several lambing periods a year to benefit from buffer and adaptive mechanisms that limit the impact of fertility fluctuation on flock productivity, (ii) a very well-controlled level of inputs to reduce production costs, even to the point of no concentrate being used if the flock's productivity is low to medium.

Authors' contribution Conceptualization MB, FJ, FB, BD, RS and CM; Software MB; Methodology MB; Formal analysis MB and FJ; Visualization MB; Writing–original draft MB; Writing–review and editing MB, FJ, FB, BD, RS and CM.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Barbieri P, Pellerin S, Seufert V, Nesme T (2019) Changes in crop rotations would impact food production in an organically farmed world. Nature Sustainability 2:378–385. https://doi.org/10.1038/s41893-019-0259-5

Belhadj SI, Chniter M, Najar T, Ghram A (2019) Meta-analysis of some physiologic, metabolic and oxidative responses of sheep exposed to environmental heat stress. Livest Sci 229:179–187. https://doi.org/10.1016/j.livsci.2019.09.026

Bellet V, Ferrand M (2014) Leviers de réduction des coûts de production en élevage ovin viande. Rencontres Recherches Ruminants 21:187–190

Benoit M (1998) A tool for simulation of sheep flock functioning, with it's economic results: a help for adaptation to new contexts. INRA Productions Animales 11(3):199–209

Benoit M, Laignel G (2011) Long term analysis of meat sheep farming systems in France. Which dynamics of evolution and which factors can explain the economical performance? Inra Productions Animales 24(3):211–220

Benoit M, Sabatier R, Lasseur J, Creighton P, Dumont B (2019) Optimising economic and environmental performances of sheep-meat farms does not fully fit with the meat industry demands. Agron Sustain Dev 39:40, 11p. https://doi.org/10.1007/s13593-019-0588-9

Blauhut V, Gudmundsson L, Stahl K (2015) Towards pan-European drought risk maps: quantifying the link between drought indices and reported drought impacts. Environ Res Lett 10(1):014008. https://doi.org/10.1088/1748-9326/10/1/014008

Botreau R, Farruggia A, Martin B, Pomies D, Dumont B (2014) Towards an agroecological assessment of dairy systems: proposal for a set of criteria suited to mountain farming. Animal 8(8):1349–1360. https://doi.org/10.1017/S1751731114000925

Carpenter S, Walker B, Anderies JM, Abel N (2014) From metaphor to measurement: resilience of what to what? Ecosystems 4(8):765–781. https://doi.org/10.1007/s10021-001-0045-9

Cordier J, Erhel A, Pindard A, Courleux F (2008) La gestion des risques en agriculture de la théorie à la mise en oeuvre : éléments de réflexion pour l'action publique. Notes et études économiques 30:33–71

Darnhofer I (2014) Resilience and why it matters for farm management. Eur Rev Agric Econ 41(3):461–484. https://doi.org/10.1093/erae/jbu012

Diakité ZR, Corson MS, Brunschwig G, Baumont R, Mosnier C (2019) Profit stability of mixed dairy and beef production systems of the mountain area of southern Auvergne (France) in the face of price variations: bioeconomic simulation. Agric Syst 171:126–134. https://doi.org/10.1016/j.agsy.2019.01.012

Dumont B, Fortun-Lamothe L, Jouven M, Thomas M, Tichit M (2013) Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 7(6):1028–1043. https://doi.org/10.1017/S1751731112002418

Gethmann J, Probst C, Sauter-Louis C, Conraths FJ (2015) Economic analysis of animal disease outbreaks - BSE and bluetongue disease as examples. Berliner Und Munchener Tierarztliche Wochenschrift 128(11–12):478–482. https://doi.org/10.2376/0005-9366-128-478

Holling C.S., 1996. Engineering resilience versus ecological resilience. In: engineering within ecological constraints. Washington, DC: 31-44

Joly F, Sabatier R, Hubert B (2018) Modelling interacting plant and livestock renewal dynamics helps disentangle equilibrium and non-equilibrium aspects in a Mongolian pastoral system. Sci Total Environ 625:1390–1404. https://doi.org/10.1016/j.scitotenv.2017.12.215

Martin G, Magne MA, Cristobal MS (2017) An integrated method to analyze farm vulnerability to climatic and economic variability according to farm configurations and Farmers' adaptations. Front Plant Sci 8:1483. https://doi.org/10.3389/fpls.2017.01483

Mosnier C (2015) Self-insurance and multi-peril grassland crop insurance: the case of French suckler cow farms. Agricultural Finance Review 75(4):533–551. https://doi.org/10.1108/afr-02-2015-0006

Mosnier C, Agabriel J, Lherm M, Reynaud A (2009) A dynamic bio-economic model to simulate optimal adjustments of suckler cow farm management to production and market shocks in France. Ecological economics 68(5):1408–1416. https://doi.org/10.1016/j.ecolecon.2008.10.001

Mosnier C, Fourdin S, Moreau J, Boutry A, Le Floch E, Lherm M, Devun J (2014) Impacts des aléas climatiques en élevages bovin et ovin allaitants et demande de couverture assurantielle. Notes et études économiques 38:73–94

Perrin JB, Ducrot C, Vinard JL, Hendrikx P, Calavas D (2011) Analyse de la mortalité bovine en France de 2003 à 2009. INRA Productions Animales 24(3):235–244

Pimm SL (1984) The complexity and stability of ecosystems. Nature 307:321–326

Sabatier R, Joly F, Hubert B (2017) Assessing both ecological and engineering resilience of a steppe agroecosystem using the viability theory. Agric Syst 157:146–156. https://doi.org/10.1016/j.agsy.2017.07.009

Tzouramani I, Sintori A, Liontakis A, Karanikolas P, Alexopoulos G (2011) An assessment of the economic performance of organic dairy sheep farming in Greece. Livestock science 141(2-3):136–142. https://doi.org/10.1016/j.livsci.2011.05.010

Urruty N, Tailliez-Lefebvre D, Huyghe C (2016) Stability, robustness, vulnerability and resilience of agricultural systems. A review Agronomy for Sustainable Development 36(1). https://doi.org/10.1007/s13593-015-0347-5

Van Kernebeek HRJ, Oosting SJ, Van Ittersum MK, Bikker P, De Boer IJM (2016) Saving land to feed a growing population: consequences for consumption of crop and livestock products. Int J Life Cycle Assess 21(5):677–687. https://doi.org/10.1007/s11367-015-0923-6

van Zanten HH, Meerburg BG, Bikker P, Herrero M, de Boer IJ (2016) Opinion paper: the role of livestock in a sustainable diet: a land-use perspective. Animal 10(4):547–549. https://doi.org/10.1017/S1751731115002694