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Economic impact of peste des petits ruminants on small ruminant production in Senegal: Gender considerations within a system dynamics modelling approach

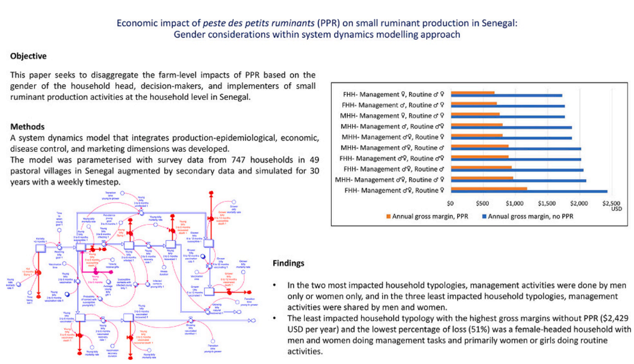
J. Aboah[a,b,*], Z.A. Campbell[c], M. Dione[a], P. Kotchofa[d], I. Guy[e], B. Wieland[f,g], M.M. Lo[h], K. M. Rich[i]

[a] International Livestock Research Institute (ILRI), West Africa Regional Office, Dakar, Senegal
[b] Commonwealth Scientific Industrial and Research Organisation, 306 Carmody Road, St Lucia, Queensland, Australia
[c] International Livestock Research Institute (ILRI), Nairobi, Kenya
[d] International Water Management Institute – Southeast Asia, C/o National Agriculture and Forest Research Institute (NAFRI), Vientiane, Lao Democratic People's Republic
[e] International Livestock Research Institute (ILRI), 01 BP 1496, Ouagadougou, Burkina Faso
[f] Institute of Virology and Immunology, Mittelhäusern, Switzerland
[g] Department of Infectious Diseases and Pathobiology, Vetsuisse Faculty, University of Bern, Switzerland
[h] Laboratoire National de l'Elevage et de Recherches Vétérinaires (LNERV), Institut Sénégalais de Recherches en Elevage (ISRA), Hann, Dakar, Senegal
[i] Oklahoma State University, Ferguson College of Agriculture, Division of Agricultural Sciences & Natural Resources, Stillwater, OK, USA

HIGHLIGHTS

- PPR leads to economic losses for affected livestock keeping households.
- The distribution of work and decision-making amongst household members is crucial for PPR eradication.
- Interventions may benefit from incorporating gender transformative approaches in communities.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Peste des petits ruminants (PPR) remains a persistent challenge for small ruminant production in Senegal, leading to economic losses for livestock keepers. Gender dynamics and socio-cultural factors influence production decisions at the household level. Despite its relevance, economic impact models of PPR have not incorporated gender dynamics.
OBJECTIVE: This paper seeks to redress this gap by disaggregating the farm-level impacts of PPR based on the gender of the household head and implementers of routine and management activities in small ruminant production at the household level.

* Corresponding author at: International Livestock Research Institute (ILRI), West Africa Regional Office, Dakar, Senegal.
E-mail address: joshua.aboah@csiro.au (J. Aboah).

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Goats
Sheep

METHODS: To quantify the gendered economic impacts of PPR, a system dynamics model was developed with four modules: integrated production-epidemiology, economics and profitability, disease control, and marketing. The model was parameterised based on survey data from 747 households in 49 agro-pastoral and pastoral villages in Senegal and augmented by secondary data. The model was validated (structurally and behaviourally) and simulated for 30 years with a weekly timestep. A set of disease scenarios were run for ten different farm household typologies based on the gender of the household head and household members who perform production management activities (like purchasing, selling, gifting, and vaccinating animals) and routine activities (like feeding, cleaning pens, and caring for sick animals).
RESULTS AND CONCLUSIONS: Model results estimated annual reductions in farm profitability of 51% to 61% with a hypothetical 25% incidence rate of PPR, corresponding to an average of $1051 to $1246 USD lost per household per year. In the two most impacted household typologies, management activities were performed by either men only or women only, and in the three least impacted household typologies, management activities were shared by men and women. The least impacted household typology with the highest gross margins without PPR ($2429 USD per year) and the lowest percentage of loss (51%) was female-headed households with men and women doing management tasks and primarily women or girls doing routine activities.
SIGNIFICANCES: Households with both women and men engaged in management activities were less impacted by PPR, highlighting the crucial role of women's agency in management decisions taken in small ruminant production at the farm level. The findings further provide the empirical grounding for considering gender dynamics in interventions to control PPR and other livestock diseases in small ruminant production systems.

1. Introduction

Small ruminant (goat and sheep) production is a source of income and nutrition and serves as an emergency fund for households in many developing countries (Alemu et al., 2019; McKune et al., 2021). However, the productivity of small ruminants can be hindered by outbreaks of diseases like peste des petits ruminants (PPR). PPR is a viral disease endemic in large parts of Africa, Asia, and the Near and Middle East (World Organisation for Animal Health (WOAH), 2024). The economic impact on food security and livelihoods makes PPR one of the most economically important diseases for people relying on small ruminants to make a living, with losses from outbreaks disproportionately affecting poor, rural households (Kotchofa et al., 2021). Annual global impacts of PPR have been estimated at between $1.4 billion and $2.1 billion USD (Food and Agriculture Organization of the United Nations and OIE World Organisation for Animal Health, 2016). The economic importance of PPR has attracted the attention of the global community, and consequently, PPR has been targeted by the international community for worldwide eradication by 2030 (Kumar et al., 2014).

At the same time, amongst the gaps in PPR research is a lack of disease impact studies that consider gender norms and other social and cultural factors (Serra et al., 2022). In a study of PPR vaccine access in Senegal, Uganda, and Nepal, the intersectional structures of inequality related to gender, geographical remoteness, and social markers including caste, ethnicity, and livelihood reduced the ability of individuals or groups to access PPR vaccines and increased vulnerability to the impacts of disease (Serra et al., 2022). Socio-cultural practices concerning the type (age, species, and sex) of animals gifted and received by households, the gender of implementors of management and routine activities in small ruminant production in the household, and the division of labour roles all influence production dynamics (e.g., differences in the flock size by species and age) and production investments like disease control (Sow et al., 2021).

Considering gender in the economic impact assessment of PPR, especially in communities at high risk of PPR outbreaks with differentiated gender roles in small ruminant production, has the potential to give more accurate impact estimates. It also strengthens and informs implementation efforts of PPR eradication strategies by identifying the people and groups most impacted by disease, allowing them to be strategically targeted in vaccination and other control activities, and enabling those most able and incentivised to take different kinds of actions to prevent or control disease. Unfortunately, incorporating gender increases model complexity and appropriate data are not always available. Existing simulation models used to assess the economic impact of PPR (El Arbi et al., 2019; Hammami et al., 2018; Lhermie et al., 2022) have not adequately considered gender.

This paper seeks to redress this gap by assessing the gender-disaggregated economic impacts of PPR by including the gender of the household head and gender of implementors of management and routine activities in small ruminant production in Senegal.

2. Methodology

2.1. Model description

A system dynamics (SD) modelling approach was adopted in this study. System dynamics models are systems of nonlinear differential equations that capture the various interactions inherent in complex systems, including technical, environmental, and institutional. These models are relevant in livestock systems given the multitude of biological lags in livestock production and such systems' interactions and feedback with epidemiological, economic, and household variables mediating system behaviour (Rich et al., 2011).

The SD model used the interactions of parameters in four modules to assess the economic impact of PPR in the absence of vaccines across ten household typologies over time. The four modules were: (i) integrated production-epidemiology dynamics, (ii) disease control, (iii) economics and profitability, and (iv) marketing. The integrated production-epidemiology module interacts with the economic and marketing modules through the outflows of animals sold that are mediated by PPR outbreaks. Higher incidence of disease reduces animal stocks and outflows for sale, reducing profitability in the short-term. In addition, as PPR particularly targets younger animals, there is a lagged reduction of available supply in the medium-term which compounds sales losses and the breeding of animals in the future.

In the marketing module, the sold animals contribute to the inflow of supply that influence the supply-demand dynamics determine the endogenized price at which animals are sold. The price variable influences the economic module through decisions to sell and/or breed animals. Additionally, the stocks of animals in the integrated production-epidemiology module determine the production cost in the economic module. The feedback interaction between the two modules was captured through the estimated gross margin in the economic module, which served as a basis for production decisions such as the feeding of animals in the integrated production-epidemiology module. The disease control module interacts with the integrated production-epidemiology module via the estimated vaccination rate, with higher levels of vaccination tamping down the incidence of PPR and inducing greater levels of animal production. Details of the model structure and equations are presented in the supplementary materials.

The model was conceptualised and parameterised based on primary and secondary data. Primary data were collected using an intra-household survey implemented by the Epidemiology and control of peste des petits ruminants (ECo-PPR) project (Wieland et al., 2020). The survey targeted men and women involved in small ruminant production and included questions about disease control, roles and responsibilities, and decision-making. Data were collected in April of 2021 from 747 households in five pastoral and agropastoral communities in Tambacounda, Saint Louis, Kaffrine, and Louga regions in Senegal. The study locations were purposively chosen as strategic for the PPR eradication initiative due to previous PPR outbreaks, proximity to international borders with Mali and Mauritania, and/or high levels of commercial or transhumant animal movement. Consequently, the sampling strategy favoured rural households with extensive production systems and the data are not designed to be nationally representative. Secondary data, mainly national-level statistics such as population growth rate, household size, and per capita consumption, came from World Bank (2021), FAOSTAT (2022), and expert elicitation. The model was developed in Stella Architect 2.5.

2.1.1. Household typologies

The model attempted to represent the diversity of households with regards to structure, demographics, and division of labour in small ruminant production by categorising them into ten typologies based on the gender of the household head and the gender of the main people performing management and routine activities in small ruminant production. This is a significant improvement on the outdated practice of only disaggregating by gender of the head of household. Female-headed households have different demographic compositions than male-headed households and targeting only women who are household heads misses contributions from married and yet-to-be married women (Beegle and Van de Walle, 2019). Differentiating between participation in management and routine activities allows for a more nuanced description of household division of labour than relying on defaults of "owner" or "household head" which easily revert to describing prevalent gender norms instead of the actual patterns within a household. Management activities denote resource control and decision-making power. They included buying, selling, slaughtering, and vaccinating animals. Routine activities are associated with less resource control and include labour-intensive and recurring tasks including feeding and caring for animals, taking animals for grazing, and identifying sick animals. Most management activities were undertaken by men and women, but routine activities were also done by girls and boys; for example, boys taking animals for grazing. For this reason, the management activities are referred to as being done by men and women and routine activities as being done by males and females, which may include boys and girls.

The ten household typologies were created through the following process. The survey data consisted of men's and women's reports of which household members performed 22 activities related to small ruminant production. These data were operationalised into five groups by dividing the activities into management and routine activities and noting whether each activity at household level had more women or girls doing it (marked female), men and boys (marked male), or equal numbers of both (marked both). The five typologies were applied across male-headed households (MHH) and female-headed households (FHH) for a total of ten typologies as presented in Table 1. For the purposes of this paper, these typologies were considered to be static (i.e., households cannot move between typologies), but a research strategy that endogenizes a more dynamic gendered household typology structure will be discussed later in the Discuss section.

The most common household typology in the ECo-PPR dataset was a male-headed household with a man performing most management activities and male and female household members doing routine activities (41% of all households). The second most common household was a male-headed household with male and female household members contributing to both management and routine tasks (23%). The most common typology for female-headed households, which made up only 7% of all households, had males and females contributing to management and routine tasks (2% of all households).

2.1.2. Integrated production-epidemiology module

The first module combined production variables describing how animals enter the flock (birth, purchase, or gifts) and exit (death, sale, theft, consumption, and gifting) with epidemiological variables such as infection rate. Animals were grouped by sex and growth stage which was connected to the epidemiological portion of the module whereby an animal's health status using a modified SIR model (susceptible-infected-recovered/ dead) was associated with their growth stage.

Given differences in the level of susceptibility to PPR by age and species, the offtake rates for sheep and goats (Sow et al., 2021), and the differences in the age at first parturition for goats and sheep (Lesnoff and Lancelot, 2010), a disaggregation of the small ruminants based on the animal species facilitated the accounting of different revenue streams. Within each sector, the animals were grouped by sex. Sheep were grouped as rams and ewes and goats were grouped as billies and nannies. Following the age stratification adopted by El Arbi et al. (2019), small ruminants transition through four growth stages: (*i*) lamb/kid stage (0–3 months); (*ii*) young animal (>3 to 6 months); (*iii*) growing animal (>6 to 12 months), and (*iv*) adult animal (>12 months).

*A*1:1 male-to-female ratio was specified for new animal births, with an estimated abortion rate of 32%. Although twinning is a reported reproduction occurrence in goats (Sow et al., 2021), a more conservative estimate of one animal birth per year was considered. Lambs that are born grow into young rams after six months, and they become ready for mating after 24 months (Gebre et al., 2014). Other than new births, animals received as gifts were another in-flow into the integrated production-epidemiology module. The main outflows in this module were deaths, animal sales, gifting of animals, and household consumption. Deaths were captured at the different transitional growth stages. Adult male animals were sold after 156 weeks; and the female animals were sold after 208 weeks (Sow et al., 2021).

Available data suggested goats were more commonly given as gifts than sheep, which were primarily sold. Thus, the model assumes only goats were received and given as gifts. The number of goats given and received (extrapolated from responses about the number of animals exchanged within the last six months) and type of goat (sex and age) given and received in the most recent exchange are described in Table 2. Giving and receiving female animals has larger implications for flock

Table 1
The frequency of each household typology.

	Management ♂♀ Routine ♂♀	Management ♂♀ Routine ♀	Management ♂♀ Routine ♂	Management ♀ Routine ♂♀	Management ♂ Routine ♂♀	Total
MHH	170 (23%)	29 (4%)	152 (20%)	38 (5%)	304 (41%)	693 (93%)
FHH	18 (2%)	8 (1%)	5 (1%)	14 (1%)	10 (1%)	54 (7%)
Total						747

MHH = Male-headed household, FHH = Female-headed household.
♂ indicates activities solely or primarily performed by men and boys, ♀ by women and girls.
Source of data: ECo-PPR.

Table 2
Mean number of goats given and received as gifts annually by household typology and sex and age of goat given in the most recent exchange.

	Management activities ♂ ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♀	Management activities ♂ ♀, Routine ♂	Management activities ♀, Routine ♂ ♀	Management activities ♂, Routine ♂ ♀
Given as gifts					
MHH	**1.81^{AF}**	2.33^{AM}	2.53^{AM}	2.38^{AM}	2.63^{AM}
FHH	2.64^{AM}	**3.52^{AF}**	1.63^{AM}	3.55^{AM}	**1.59^{AF}**
Received as gifts					
MHH	1.4^{YM}	1.4^{YM}	1.7^{YM}	2.3^{AM}	1.7^{YM}
FHH	1.8^{YM}	1.6^{YM}	2.0^{YM}	1.6^{AM}	**2.0^{YF}**

MHH = Male-headed household, FHH = Female-headed household.
♂ indicates activities solely or primarily performed by men and boys, ♀ by women and girls.
AM Adult male goat: ^{AF} Adult female goat.
YM Young male goat: ^{YF} Young female goat.
Household typologies that exchanged female goats in the most recent exchange are **bolded.**
♂ indicates activities solely or primarily performed by men and boys, ♀ by women and girls.
Source of data: ECo-PPR.

growth potential so the figures for the four household typologies that gifted female goats in the most recent exchange are bolded. It was assumed in the model that only healthy animals were given as gifts.

The epidemiological aspect of the module highlighted the health status of the animals at the different growth stages. The state of the animals was classified as susceptible animals (S); animals that were exposed to the PPR virus became infected (I) and either recovered (R) or died (D). The uninfected animals became susceptible at the next growth stage. Susceptible animals were infected based on the contact rate and the prevalence rate (El Arbi et al., 2019) of the total animal population. An infected animal was assumed to recover after 10 days (i.e., after the incubation, clinical disease, and recovery period) (Kumar et al., 2014) at an estimated mortality rate of 0.1.

2.1.3. Disease control module

The disease control module captured the interaction between socioeconomic, production, and financial variables and how these interactions influenced household disease control. Vaccination was the focal disease control mechanism. The vaccination coverage in a given year was predicated on either one or both conditions: (*i*) the availability and access to vaccines, which was influenced by the profitability of the farm in the previous year; and *(ii)* whether the cost of vaccination was fully or partially covered by an external agency (e.g., government or non-governmental organisation). The time to deploy the vaccine was captured in the model for the different ages of the animal. Given the aim of this paper, a vaccine-naïve population was assumed and no PPR vaccination took place. The impact of vaccination was addressed in a separate paper (Aboah et al., 2023).

2.1.4. Economic module

The economic module was segmented into two parts – production cost and revenue components. Feeding costs were omitted from this model, as feed sources were assumed to be from grazing, crop residues, or scraps, while only family labour was assumed for management. The model structure has the ability to capture different production costs in settings where these are more relevant.

Two outputs from the economic module - gross margin (USD) and margin of economic loss (%) - are the focal outputs for the economic impact discussion. The gross margin earned by the households was estimated as the difference between the total revenue in the revenue sector and the total production cost in the production sector as shown in Eq. 1. Household production investments were specified as a short-term expectation of annual profit (52 weeks). Household production investment levels in a given year (expressed as a binomial parameter – yes/no) were conditioned on the profit of the preceding year exceeding zero. Therefore, the expected production investment was specified as the first-order exponential smoothing of the gross income. The margin of economic loss is expressed as a percentage change in gross margin due to PPR-related deaths (Eq. 2).

$$\text{Gross margin} = \sum \text{Price}^{*}\text{Quantity}_{(\text{sold animals})} - \sum \text{Production Cost} \tag{1}$$

$$\text{Loss}_{(\text{margin})} = (\Delta\ \text{Gross margin}/\text{Gross margin})^{*}100 \tag{2}$$

A paired sample *t*-test was estimated (as shown in Eq. 3) for the different household typologies to establish significant differences in the margin of economic loss for the different household typologies due to PPR.

$$\text{t} = \sum \left(\mu_{(\text{Household I})} - \mu_{(\text{Household II})}\right) \Big/ \text{s} \Big/ \sqrt{\text{n}}\Big) \tag{3}$$

where t, μ, s, n represent the t-test, mean, standard deviation, and sample size, respectively. The t-test estimation was performed in the R software, after exporting the margin of economic loss generated from the Stella Architect software.

2.1.5. Marketing module

The marketing module describes the supply and demand of small ruminants nationally. The market supply of small ruminants was extrapolated using the average number of animals sold by individual households based on historical production data, the population of livestock farm households (29.5%) (Habanabakize et al., 2022), and an average household size of seven people (World Bank, 2021). Following Mtimet et al. (2021), the aggregate demand for small ruminants was determined using the average carcass weight and estimated weekly demand for meat using an elasticity of demand for lamb and goat meat of 0.8 (Bouyssou et al., 2024). From 2010 to 2018, the annual population growth in Senegal was 2.7%, and the total population size as of 2021 was estimated at 17,196,308 (World Bank, 2021). Based on this, a growth rate of 2.7% was applied to the model to capture the dynamics of population growth.

The unit prices for goats and sheep were endogenized based on the aggregate demand and supply for small ruminants. The unit prices of sheep and goat meat[1] were determined using a price change of twice per year. Table 3 shows a summary of key parameters in the model. The SD model was simulated for 30 years with a weekly timestep. The outbreak was seeded after 260th week (fifth year), to allow for herd dynamics in early time periods to generate a consistent trend (Lesnoff and Lancelot,

[1] The average producer prices for goat and sheep meat from 2010 to 2019 were 1061 and 1703 FCFA francs per kilogram, respectively (FAOSTAT), or \$1.59 and \$1.61 USD per kilogram.

Table 3
Selected model parameters.

Parameter	Value	Module	Source
Average flock size	16 (i.e., 2 animals) for each growth stage	Integrated production-epidemiology (PE)	ECo-PPR household survey
Daily weight gained by animals	62 g per day		FAOSTAT, 2022
Prevalence rate (infection)	0.25		El Arbi et al., 2019
Contact rate	1		Assumed
Offtake rate for young ewe	0.2		ECo-PPR household survey
Gestation period	37.5 weeks		Lesnoff and Lancelot, 2010
Average PPR illness duration	3 weeks		WOAH, 2024
Time to keep ewes	104 weeks		Sow et al., 2021
Time to sell bred back nannies	208 weeks		Sow et al., 2021
USD-CFA exchange rate	0.0015	Economic	Xe.com (Nov. 2022)
Abortion rate	32%	PE	ECo-PPR household survey
Ram to Ewe birth ratio	0.5	PE	ECo-PPR household survey
Household consumption rate	20%	Marketing	ECo-PPR household survey
Price elasticity of demand for lamb and goat meat	0.8	Marketing	Bouyssou et al., 2024
Farm household proportion into livestock production	29.5%		Habanabakize et al., 2022

2010).

2.2. Model validation

The model validation sequence (Barlas, 1996) was followed to validate the model structure and behaviour. The check unit function of the Stella Architect software® was used to validate the unit consistency. The model structure in terms of the biological growth progression of small ruminants was first validated by referencing the literature. Secondly, a reference group of experts were consulted to validate the integration of the epidemiological considerations into the production aspects of the model.

For the structure-oriented behaviour test, a production-related extreme-conditioned test was conducted involving twinning for every animal birth and no new births. Fig. 1 shows the model behaviour (using the total sheep and total goats as a focal indicator) when the production extreme conditions were applied. The top graphs in Fig. 1 show no twinning. As expected, the twinning conditions caused the total number of animals to increase as shown by the middle graphs, while no new births caused a decline in the total number of sheep and goats owned by households, as shown in the bottom graphs. Although the total sheep population runs to zero, there are some goats remaining because the model incorporated goats received as gifts.

2.3. Model assumptions

In the integrated production-epidemiology module, the following were assumed: (a) one animal birth per year for sheep and goats, (b) that only healthy goats are given and received as gifts, and (c) an equal (1:1) sex ratio for new births of animals. Deviations from this equal sex ratio can significantly influence the overall herd size; a higher proportion of female births, for example, would eventually result in a larger herd size compared to a scenario with a higher proportion of male births. The model also assumed an equal probability of natural mortality regardless of the health status of the animal—whether it is susceptible, infected, or recovered. This assumption simplifies the analysis by treating natural mortality as an independent factor, irrespective of the specific health condition of the animals in the herd.

In the disease control module, we assumed a vaccine-naïve population and no PPR vaccination. In reality, Senegal has invested in vaccination campaigns for PPR with estimated national coverages of 14% and rates as high as 86% in targeted areas following vaccination activities, such as in Saint Louis in the 2010–2011 campaign. Amongst the study respondents, 35% reported having used PPR vaccines at least once (Tago et al., 2017).

In the economic module, it was assumed that livestock keepers do not pay for small ruminant feed. There was no mechanism in the model to monetise the labour costs of small ruminant production, such as time spent taking animals for natural grazing. Likewise, the marketing model assumptions were based on the accuracy of the parameters selected as shown in Table 3.

Another assumption in the model concerned the static nature of household typologies, implying that households do not transition from one typology to another. Marriage, divorce, or death of a spouse are the ways to transition from a male-headed to female-headed household and vice versa, however given marriage is the norm (94.6% of ECo-PPR respondents reported being married), it was assumed that the overall rates of marriage and therefore ratios of female to male-headed households remained constant. A more interesting question is what drives transitions between different patterns of gendered divisions of labour and decision-making, a phenomenon that certainly occurs, but is influenced by cultural norms and socio-cultural factors beyond the ability of current data to quantitatively describe. This will be addressed further in the discussion section, but suffice it to say, the model presented assumed no transitions between household typologies.

3. Results

3.1. Impact of PPR on the margin of economic loss

Results of the household-level economic impact following a modelled introduction of PPR at a 25% incidence rate into a vaccine-naïve population are presented and discussed in this section. The annual gross margins with and without PPR were assessed for the ten household typologies in absolute terms (USD) and relative terms (%). The trends of the gross margin over time for the different household typologies are presented in Appendix A. Small ruminant production was an economically viable venture for all households as evidenced by the positive annual gross margins. Without PPR, annual gross margins were estimated from $1726 to $2429 USD, with variations by household typology (Table 4). When PPR was introduced, the gross margin decreased by a range of 51% to 61%, equivalent to $1051 to $1246 USD respectively, and resulting in new, reduced gross margins ranging from $675 to $1183 USD.

Households with the most income from small ruminants had lower relative losses in percentage terms, but because the total income was higher, they lost more in absolute terms (gross margin loss in USD). For example, the household typology with the highest annual gross margin, estimated at $2429 USD, was a female-headed household with men and women performing management activities and women and girls performing routine activities. This household typology lost the lowest percentage of annual gross margin when PPR was introduced (51%) but lost the highest absolute amount (average losses estimated at $1183 USD).

Notably, the two most impacted household typologies had management activities done by men only or women only, and the three most

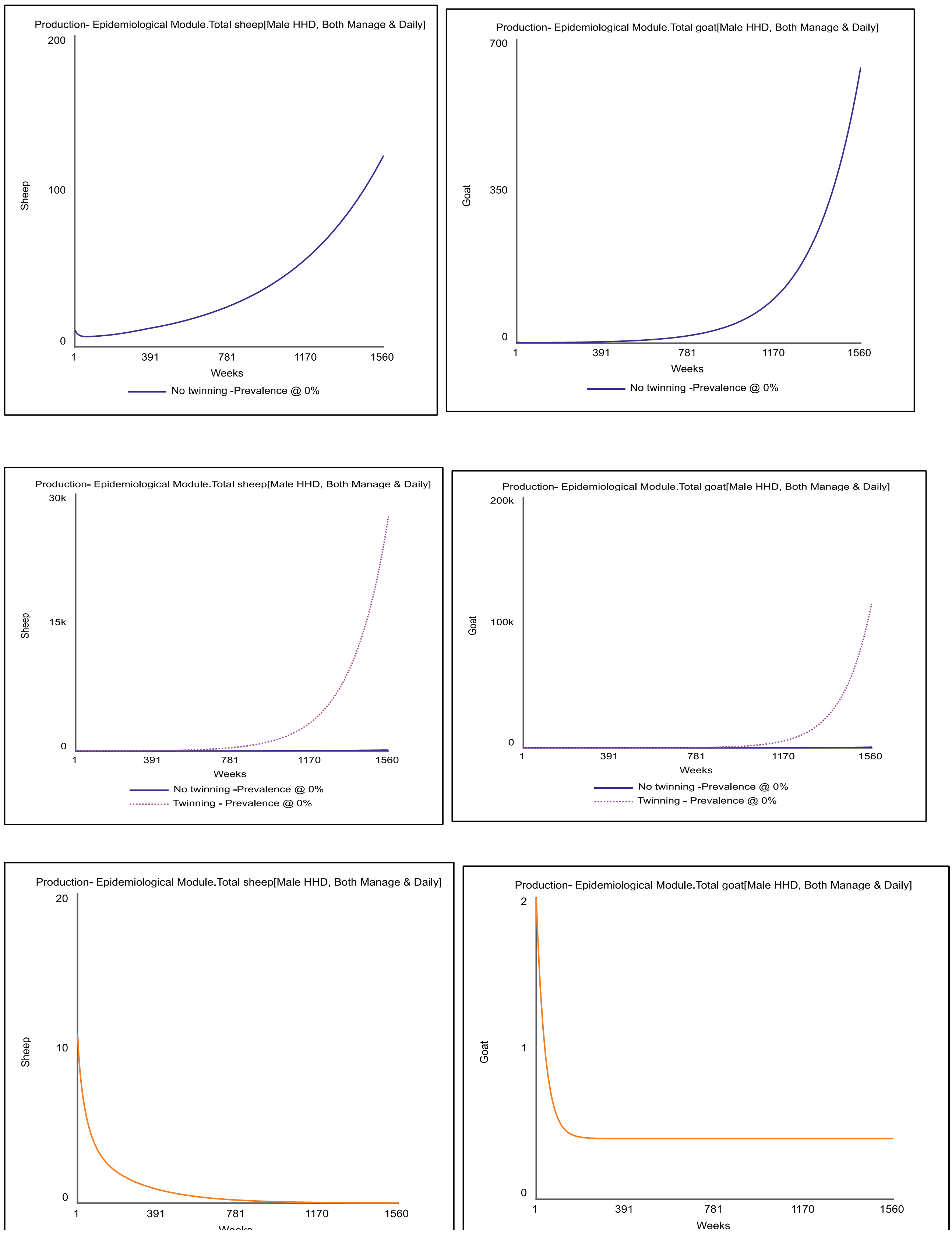

Fig. 1. Model behaviour under the production-related extreme conditions of no new animal births and twinning at each birth.

Table 4
Annual gross margins without PPR and estimated losses with PPR for ten household typologies.

Ranking gross margin loss (%)	Household typology	Gross margin loss, withPPR (%) [mean ± SE]	Gross margin loss with PPR (USD) [mean ± SE]	Annual gross margin, no PPR (USD) [mean ± SE]	Annual gross margin, PPR (USD) [mean ± SE]
1st	FHH-Management ♀, Routine ♂♀	60.9% ± 0.3%	$1051 ± $6.9	$1726 ± $23	$675 ± $16.1
2nd	FHH-Management ♂, Routine ♂♀	59.8% ± 0.3%	$1057 ± $ 6.9	$1768 ± $23	$711 ± $16.1
3rd	MHH-Management ♀, Routine ♂♀		$1013 ± $ 6.9	$1768 ± $23	$755 ± $16.1
	MHH-Management ♂, Routine ♂♀	57.3% ± 0.3%	$1075 ± $8.1	$1877 ± $27	$802 ± $18.9
	MHH-Management ♂♀, Routine ♀				
4th	MHH-Management ♂♀, Routine ♂	55.7% ± 0.3%	$1125 ± $9.3	$2020 ± $31	$895 ± $21.7
	FHH-Management ♂♀, Routine ♂♀				
5th	FHH-Management ♂♀, Routine ♂	54.1% ± 0.3%	$1112 ± $9.6	$2056 ± $32	$944 ± $22.4
	MHH-Management ♂♀, Routine ♂♀		$1135 ± $9.6	$2099 ± $32	$964 ± $22.4
6th	FHH-Management ♂♀, Routine ♀	51.3% ± 0.2%	$1246 ± $8.1	$2429 ± $41	$1183 ± $32.9

1st = most impacted; 5th = least impacted.
Assumes 25% incidence rate of PPR.
MHH is male-headed household, FHH is female-headed household.
♂ indicates activities solely or primarily performed by men and boys, ♀ by women and girls.
Figures presented ± standard error, minor discrepancies due to rounding.
Pairwise comparisons between household typologies showed statistically significant differences ($p < .001$) between the five ranked groups but not within groups (Table 5).

resilient household typologies had management activities shared by men and women. Two household typologies stand out because they were most impacted by PPR, standing to lose an estimated 61–60% of their annual profit from small ruminant production, as shown by the first and second most impacted ranking in Table 4. These were female-headed households with males and females performing routine tasks but men only or women only performing management tasks. Fig. 2 shows the value of the mean annual gross margin and the value of the loss due to PPR.

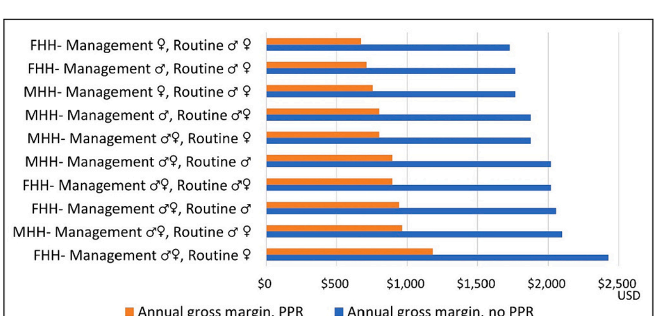

Fig. 2. Mean gross margins with and without PPR by household typology.

3.1.1. *Pairwise comparison of gross margin loss for different household typologies*

Table 5 shows the results of the within-household typologies pairwise comparison for the proportion of gross margin loss due to PPR. For most of the within-household pairwise comparison, there was a statistically significant difference in the margin of gross margin loss due to PPR except for three pairwise comparisons (all for male-headed households). For male-headed households, the within-group analysis shows a statistically significant difference in the margin of gross margins loss due to PPR for all households except these household pairs:

(i) Male-headed households where both men and women perform management activities and routine activities are mostly performed by female household members versus male-headed households where management activities are performed by women and both male and female household members perform routine activities.
(ii) Male-headed households where both men and women perform management activities and routine activities are mostly performed by female household members versus male-headed households where women perform management activities and routine activities are performed by both male and female household members.
(iii) Male-headed households where both men and women perform management activities and routine activities are mostly performed by female household members versus male-headed households where women perform management activities and routine activities are performed by both male and female household members.

For female-headed households, the results of the within-group analysis show a statistically significant difference in the margin of gross margin loss due to PPR for all the pairwise comparisons of the different households.

The results of the across-household typologies pairwise comparison, presented in Table 6, indicate that only two out of the 25 across-household pairs showed no statistically significant difference in the gross margin loss due to PPR. The household pairs with no statistically significant difference include:

(i) Male-headed households where management activities are performed by both men and women and routine activities are performed by both male and female members versus female-headed households where management activities are performed by both men and women and routine activities are performed by mostly male members.
(ii) Male-headed households where management activities are performed by both men and women and routine activities are performed by mostly male members versus female-headed households where management activities are performed by both men and women and routine activities are performed by both male and female members.

4. Discussion

Modelling the economic impact of PPR on different household typologies highlighted the way household demographics and gendered distribution of roles and responsibilities influenced the households' vulnerability to livestock disease, as expressed by changes in gross margin. Households with greater investment and profits from small ruminants use more effort and/or resources to protect their investment when PPR occurs. The household typologies with the lowest percentages

Table 5
Pairwise comparisons of margin of economic loss (within-household typologies).

Within-household typology analysis: margin of economic loss for male-headed households

	Management activities ♂ ♀, Routine ♂ ♀ Vs. Management activities ♂ ♀, Routine ♀	Management activities ♂ ♀, Routine ♂ ♀ Vs. Management activities ♂ ♀, Routine ♂	Management activities ♂♀, Routine ♂♀ Vs. Management activities ♀, Routine ♂♀	Management activities ♂♀, Routine ♂ ♀ Vs. Management activities ♀, Routine ♂♀	Management activities ♂♀, Routine ♀ Vs. Management activities ♂♀, Routine ♂	Management activities ♂ ♀, Routine ♀ Vs. Management activities ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♀ Vs. Management activities ♀, Routine ♂♀	Management activities ♂ ♀, Routine ♂ Vs. Management activities ♂, Routine ♂♀	Management activities ♂♀, Routine ♂ Vs. Management activities ♂, Routine ♂♀	Management activities ♀, Routine ♂♀ Vs. Management activities ♂, Routine ♂♀
t	−8.54	−4.33	−8.45	−8.54	4.23	0.09	0	−4.14	−4.23	−0.09
df	3096.1	3112.9	3095.8	3096.1	3112.1	3118	3118	3111.9	3112.1	3118
p-value	$<2.2e^{-16}$	$1.56e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$2.38e^{-05}$	0.93	1	$3.55e^{-05}$	$2.38e^{-05}$	0.93

Within-household typology analysis: margin of economic loss for female-headed households

	Management activities ♂ ♀, Routine ♂ ♀ Vs. Management activities ♂ ♀, Routine ♀	Management activities ♂ ♀, Routine ♂ ♀ Vs. Management activities ♂ ♀, Routine ♂	Management activities ♂ ♀, Routine ♂♀ Vs. Management activities ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♂ ♀ Vs. Management activities ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♀ Vs. Management activities ♂ ♀, Routine ♂	Management activities ♂ ♀, Routine ♀ Vs. Management activities ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♀ Vs. Management activities ♀, Routine ♂ ♀	Management activities ♂ ♀, Routine ♂ Vs. Management activities ♂, Routine ♂ ♀	Management activities ♂♀, Routine ♂ Vs. Management activities ♂, Routine ♂ ♀	Management activities ♀, Routine ♂♀ Vs. Management activities ♂, Routine ♂ ♀
t	12.45	4.24	−12.98	−10.13	−8.23	−25.08	−22.32	−17.14	−14.31	2.85
df	3075.3	3112.7	3061.4	3081.6	3099.6	2934.8	2969.5	3024.1	3050.1	3115.6
p-value	$<2.2e^{-16}$	$2.29e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	0.004

♂ indicates activities solely or mostly performed by men and boys, ♀ by women and girls.

Table 6
Pairwise comparisons of margin of economic loss (across-household typologies).

Across-household typology analysis: margin of economic loss										
	MHH-Management activities ♂ ♀, Routine ♂ ♀ Vs. FHH- Management activities ♂ ♀, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♂ ♀ Vs. FHH-Management activities ♂ ♀, Routine ♀	MHH-Management activities ♂ ♀, Routine ♂♀ Vs. FHH-Management activities ♂♀, Routine ♂	MHH-Management activities ♂ ♀, Routine ♂ ♀ Vs. FHH-Management activities ♀, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♂, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♂ ♀, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♂ ♀, Routine ♀	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♂♀, Routine ♂	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♀, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♀ Vs. FHH-Management activities ♂, Routine ♂ ♀
t	−4.33	8.14	−0.08	−17.21	−14.39	4.23	16.60	8.46	−8.78	−5.93
df	3112.9	3099.3	3118	3024.7	3050.6	3112.1	3039.5	3095.8	3091.3	3104.8
p-value	$1.56e^{-05}$	$5.64e^{-16}$	0.93	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.38e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$3.44e^{-09}$

Across-household typology analysis: margin of economic loss										
	MHH-Management activities ♂ ♀, Routine ♂ Vs. FHH-Management activities ♂ ♀, Routine ♂♀	MHH-Management activities ♂ ♀, Routine ♂ Vs. FHH-Management activities ♂ ♀, Routine ♀	MHH-Management activities ♂ ♀, Routine ♂ Vs. FHH-Management activities ♂♀, Routine ♂	MHH-Management activities ♂ ♀, Routine ♂ Vs. FHH-Management activities ♀, Routine ♂ ♀	MHH-Management activities ♂ ♀, Routine ♂ Vs. FHH-Management activities ♂, Routine ♂ ♀	MHH-Management activities ♀, Routine ♂♀ Vs. FHH-Management activities ♂ ♀, Routine ♂ ♀	MHH-Management activities ♀, Routine ♂♀ Vs. FHH-Management activities ♂ ♀, Routine ♀	MHH-Management activities ♀, Routine ♂♀ Vs. FHH-Management activities ♂♀, Routine ♂	MHH-Management activities ♀, Routine ♂♀ Vs. FHH-Management activities ♀, Routine ♂ ♀	MHH-Management activities ♀, Routine ♂♀ Vs. FHH-Management activities ♂, Routine ♂ ♀
t	0	12.45	4.24	−12.98	−10.13	4.14	16.50	8.36	−8.86	−6.01
df	3118	3075.3	3112.7	3061.4	3081.6	3111.9	3039	3095.5	3091.6	3105
p-value	1	$<2.2e^{-16}$	$2.29e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$3.55e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.07e^{-09}$

Across-household typology analysis: margin of economic loss					
	MHH-Management activities ♂, Routine ♂ ♀ Vs. FHH- Management activities ♂ ♀, Routine ♂ ♀	MHH-Management activities ♂, Routine ♂ ♀ Vs. FHH-Management activities ♂ ♀, Routine ♀	MHH-Management activities ♂, Routine ♂♀ Vs. FHH-Management activities ♂♀, Routine ♂	MHH-Management activities ♂, Routine ♂ ♀ Vs. FHH-Management activities ♀, Routine ♂ ♀	MHH-Management activities ♂, Routine ♂♀ Vs. FHH-Management activities ♂, Routine ♂ ♀
t	4.23	16.60	8.46	−8.78	−5.93
df	3112.1	3039.5	3095.8	3091.3	3104.8
p-value	$2.38e^{-05}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$3.4e^{-09}$

♂ indicates activities solely or mostly performed by men and boys, ♀ by women and girls; MHH = Male-headed household & FHH = Female-headed household.

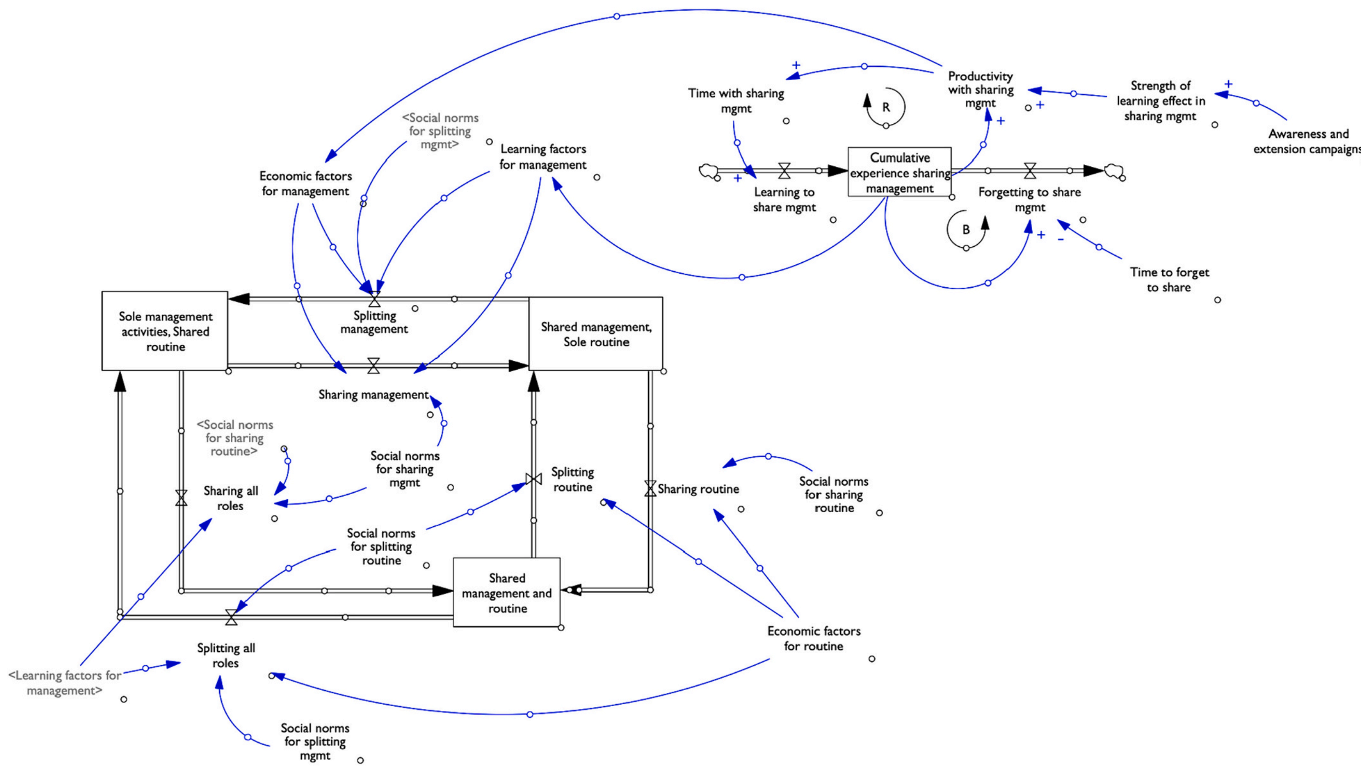

Fig. 3. A prospective model of dynamic household typologies.

of losses were those with both men and women participating in management activities together. The findings are supported by the observations made by Kariuki et al. (2022) and Namatovu et al. (2022) that farm households are better off when women are empowered to take decisions and receive support from men.

Household typologies likely influenced the incentives for investing in and prioritising small ruminant production. Social norms that restrict women from owning and managing larger livestock such as cattle and camels and competing economic opportunities for men may explain why the household typology with the highest gross margin ($2429 USD annually) was associated with a female-headed household where women and men do management activities and women do most routine activities. A female head of household with support from male family members such as adult sons, brothers, or former in-laws is in a good position to keep small ruminants in a socially acceptable way and may have limited other economic opportunities, especially in a pastoral context. The power dynamics amongst household members can influence the willingness of household members to involve themselves in small ruminant production. Kariuki et al. (2022) found the exercise of ownership and decision-making in male-headed households tended to restrict female involvement. Likewise in Ghana, Omondi et al. (2022) reported that asset ownership and the ability to contribute to livestock production decisions were strongly associated with women empowerment.

In this paper, the evaluation of gross margin did not account for the cost of family labour or outside labour such as employing a herder. This omission may manifest in a number of ways that further research should address in more depth. Labour is an important factor that varies by household typology, and with specialised roles for men, women, boys, and girls, the absence of any group means certain tasks will be left undone. For instance, without support of men or boys in the household, a woman may have trouble moving animals to a vaccination point due to restrictive social norms, competing domestic responsibilities such as caring for young children, and the physical challenges of controlling an unwieldy flock especially one containing large animals such as cattle or camels. Women are often in charge of routine production activities like feeding and taking care of sick animals, so in the absence of women who are engaged and incentivised to care for their household's livestock, animals may be more vulnerable to disease. In addition, household structure dictates in many cases what type of labour was available and likely influences the extent to which households were able to invest in small ruminant production. Finally, out-migration, particularly of men, may have important ramifications on household labour dynamics and modelling both push and pull effects of such migration, and the ability (or not) of households to substitute for such labour either within the household (by women or men) or externally in outside labour markets is an important consideration for future modelling.

The model assumption that household typologies are static raised questions about the real-world forces that contribute to changes in patterns of decision-making and labour distribution between women and men at the household level. In reality, women's participation in the labour market and by extension, in livestock management activities, may be on the rise driven by forces including rising costs of living, male labour migration, and legal reforms (Petesch et al., 2018). While quantifying the rates of these changes in gender norms and practices is beyond the scope of this paper, the metrics used to generate household typologies could be adapted to measure changes over time in response to external shocks such as drought or political reforms or development interventions that aim to address or challenge discriminatory gender norms.

Such dynamics can be handled within a system dynamics framework, though will require more robust survey and data collection instruments to tease these factors out. Previous research in other settings guides such a prospective research agenda. Berends et al. (2021) for instance looked at the transition of producers in and out of different production systems in the pig value chain in Myanmar based on the profitability and attractiveness of alternative institutional forms (e.g., producer groups and organizations). Similarly, using a model of adoption, Ulli-Beer et al. (2007) explored the consumers into and out of different acceptance regimes in participating in local recycling schemes in Switzerland based on social norms and economic effects. Drawing from these papers, Fig. 3 provides an abstracted stock-and-flow diagram that highlights the potential transitions of households into and out of different typology regimes based on own- or shared-management and routine duties within in a household. These transitions could then be parameterized by social norms (Ulli-Beer et al., 2007), economic factors, and learning effects that facilitate or impede movement to more "equitable" dynamics. In Fig. 3, a simple learning curve model based on Morrison (2008) is used to highlight the influences of learning dynamics on management which itself could be impacted by external awareness or extension campaigns.

The model presented here assumes no PPR vaccination, even though the model structure allows for these data to be used as demonstrated in Aboah et al. (2023). Incorporating some levels of vaccination would reflect the policy environment in Senegal where there is government investment in PPR vaccination and could be used to investigate whether the estimated production edge of households with women active in management would erode given the gendered barriers women can face in accessing livestock vaccines. These include cultural and social barriers to moving animals to vaccination parks, low proportion of woman animal health care workers, and costs associated with accessing privately distributed vaccines (McKune et al., 2021).

Lastly, the socio-cultural practices of giving and receiving small ruminants based on the sex, age, and species of small ruminant (goat or sheep) was highlighted as a factor that influenced production dynamics and economic returns for farm households. Although sheep have more market value than goats (Sow et al., 2021), goats are generally the preferred species that are mostly given and received as gifts. Male goats, especially young ones, are the best gift choice for slaughter, but female animals may also be gifted if the goal is to contribute to the productivity of the recipient's flock, such as a female goat given to a newly married person. Three of the four household typologies that reported gifting or receiving a female goat in the most recent exchange were female-headed households. While gifting female animals does not benefit the growth of the flock size in the long term, giftable female animals may be an asset available to women heads of household to build and strengthen social or economic relationships that benefit her in other ways.

5. Conclusion

This paper sought to examine the economic impact of PPR disease on the of changing gross margin of farm households raising sheep and goats in Senegal. The paper represents one of few attempts to incorporate gender dynamics in small ruminant production into a system dynamics model by creating household typologies based on the gender of head of household and gender of household members doing management and routine activities. The typologies encompassed elements of labour availability, power dynamics between household members that influence who can make management decisions, and gender norms that influence the types of competing economic activities available to women and men. Household typologies with only men or only women participating in management activities had the highest percentages of economic loss when PPR was introduced in the model. Female-headed households were not necessarily more vulnerable to losses. In fact, the most resilient household typology with the lowest relative losses and highest earnings from small ruminants without PPR was a female-headed household with men and women making management decisions. This is suggestive of a woman with support from male family members keeping small ruminants as a primary source of livelihood. Her ability to access PPR vaccines and other veterinary inputs, a question not addressed by this model which assumed no vaccination, is extremely relevant to implementors of any vaccination or disease control activity.

Future research could model the *ex-ante* impact of different vaccination scenarios on farm household profit and the impact of different household head behaviour towards disease mitigation and uptake of vaccines. Another possible model extension could explore the drivers of transition from one household typology to another and the impact of such transitions. This would be useful in the context of measuring the impact of gender-transformative approaches designed to challenge discriminatory and restrictive gender norms that limit women's abilities to benefit from and control livestock resources and access appropriate veterinary products and services such as PPR vaccines.

Ethical review

The ethical clearance for the survey conducted under the Epidemiology and control of peste des petits ruminants (ECo-PPR) project was approved by ILRI's Institutional Research Ethics Committee, reference ILRI-IREC2020-16.

CRediT authorship contribution statement

J. Aboah: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Z.A. Campbell:** Conceptualization, Data curation, Visualization, Writing – review & editing. **M. Dione:** Conceptualization, Data curation, Project administration, Resources, Supervision, Writing – review & editing. **P. Kotchofa:** Investigation, Writing – review & editing. **I. Guy:** Investigation, Writing – review & editing. **B. Wieland:** Conceptualization, Investigation, Writing – review & editing. **M.M. Lo:** Conceptualization, Investigation, Project administration. **K.M. Rich:** Conceptualization, Methodology, Software, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest that may be affected by the research reported in the enclosed paper.

Data availability

Data will be made available on request.

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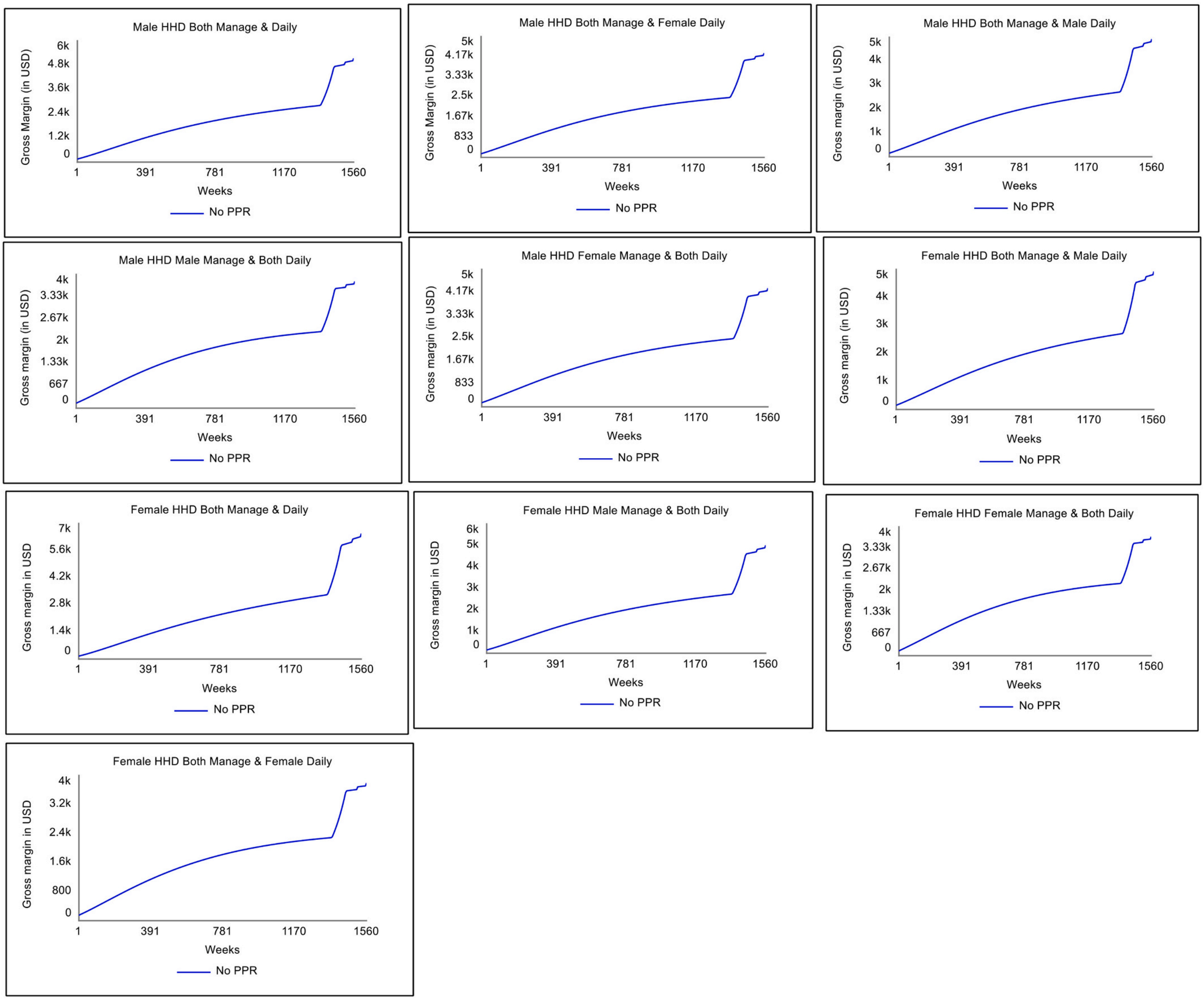
Appendix A. Gross margin trends of the different household typologies



Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103928.

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