BAE
Bio-based and Applied Economics

AIEAA
ASSOCIAZIONE ITALIANA DI ECONOMIA AGRARIA E APPLICATA

OPEN ACCESS

Citation: Wane A., Mballo A.D., Dzoukou Homsi C.L., Diakhaté P., Memboup R. (2023). Reducing food-related economic loss to improve food security and cattle trade in the Sahel: the case of agropastoral systems in Senegal. *Bio-based and Applied Economics* 12(3): 243-259. doi: 10.36253/bae-13521

Received: August 9, 2023
Accepted: August 24, 2023
Published: October 15, 2023

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Editor: Donato Romano

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Reducing food-related economic loss to improve food security and cattle trade in the Sahel: the case of agropastoral systems in Senegal

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Abstract. Food loss is a critical issue in Africa, but investigation has mainly been limited to quantity loss. Economic losses are likely to be more significant but are widely ignored. Regarding ruminant-related losses, it remains challenging to identify the optimal harvest point. Focusing on Sahelian agropastoral systems, where stakeholders operate in a shock-prone environment, our paper explains how critical actor behaviour is, and it addresses economic losses on live-animal transactions while integrating market behaviours into the analysis. Loss elimination being illusory in such a context, our findings pioneer a loss reduction approach that is supported by an appropriate optimisation programme tested on primary data collected from 202 agropastoral households in Senegal.

Keywords: behaviours, economic loss, optimal loss, pastoralism, Sahel.
JEL codes: C61, D13, Q12, Q13, R20.

HIGHLIGHTS

- Post-harvest losses in African livestock and pastoral systems are narrowly limited to loss of physical quantity of product while loss of economic value is largely ignored.
- Livestock multifunctionality and behaviours of individual actors in increasing uncertainty led Sahelian pastoralists to behave with a bounded rationality.
- An optimization model subject to pastoral constraints allows for the determination of the optimum number of animal species that must be sold to cover household expenditures and animal loss.
- Simulation of ad hoc loss reduction scenarios reconciles food security and competitiveness of livestock economics in the Sahel.

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1. INTRODUCTION

A growing local and regional demand for meat and milk has provided opportunities for pastoral producers in the Sahel. However, several factors make it difficult for Sahelian producers and other actors in the livestock value chain to take full advantage of this positive trend. Ickowicz et al. (2012), Hollinger and Staaz (2015), and Diawara et al. (2017) all highlight low herd productivity as a critical constraint. Together with structural constraints relating to logistics, infrastructure, public policy and enabling environment, low productivity contributes to sub-optimal performance in the livestock sector. The Sahelian livestock sector is vulnerable to multifaceted shocks, mainly relating to climate, disease, natural disasters and market fluctuations. Some of these shocks are severe, leading to quantitative, qualitative and economic loss (IFAD 2016).

There is ongoing interest in this issue, even though there is scarcity of information and the evidence on the extent of the losses is mixed with estimates ranging from 2% up to 27% (FAO, 2011; Blanchard et al., 2016).

A quantitative evaluation of the different types of loss remains challenging for several reasons. While productivity gaps have been documented, food loss in the livestock sector has received far less attention. Comprehensive modelling methods are needed to clarify spatial and temporal fluctuations in loss rates and to make credible estimates of the quantitative, qualitative and economic losses. Further complicating the situation in the Sahel is the perceived dualism between commercial and communal livestock keepers and between modern and traditional systems (Lyet et al., 2010). The structure of the livestock value chain is extremely nuanced. There are considerable differences in the levels of market integration, motivation and vulnerability among value chain actors, and this influences the nature and perceptions of loss. Furthermore, small-scale producers have a ‘producer–consumer model,’ as articulated by Chayanov (1926, 1990). The goal of pastoralists in a changing environment, such as the Sahel, is to balance short-term consumption needs with long-term herd-building strategies to meet future consumption demands (Fadiga, 2013). Consequently, an understanding of the motivation to increase sales is key to understanding decision-making strategies. Moreover, the parameters of the livestock market remain relatively rigid, with a low supply of animals and high price levels.

Food loss has adverse effects on food safety and security, particularly for poor and vulnerable people (Sheahan and Barrett, 2016), on the livestock market (Wane and Mballo, 2016) and on sustainable development (Gustavsson, 2011).

Concerns about food loss frequently give rise to quantitative and qualitative estimates, which tend to be followed by remediation (in a ‘zero loss’ approach). However, when considered from a different economic perspective, not all loss is undesirable. This opens the opportunity to explore an exciting loss assessment method in which mitigation is the goal (an ‘optimal loss’ approach). The optimal loss approach is based on two key assumptions. First, the cost of total elimination of loss is prohibitive, regardless of the availability of technology and institutional arrangements. Second, a certain level of loss is inevitable and not necessarily undesirable, particularly in the agricultural sector.

This paper contributes to a long-standing debate on risk in the agricultural sector (Wane and Mballo, 2016; Chavas et al., 2021) and decision-making related to risk perception (Wane et al., 2020).

To address the complex issue of loss in the Sahelian pastoral areas, we used a sequential approach by which qualitative data was collected from approximately 15 people in each of the three targeted sites, and these results guided the subsequent collection of quantitative data from 202 households.

This paper pioneers the idea that it is possible to improve food security in the Sahelian region by minimizing losses in the production stage of the live animal value chain. The paper contributes by developing an optimisation model that determines the optimum numbers of different animal species to be sold to counteract losses while also being subject to the farmers’ constraints. Our methodology is pragmatic in that the recommended optimisation approach aims for loss reduction rather than illusory loss eradication. In addition, unlike measures of loss in the crop sector, which focus entirely on post-harvest losses, in our analysis of loss in the livestock sector, we consider both pre-market and market losses to be equally significant. Second, our model shows the ideal sales volume, age at sale and price at sale that will allow the livestock farmer to generate sufficient income to cover his expenditure. Third, we simulate loss reduction scenarios, with their effects on volume and market price parameters, and we show how these scenarios can result in a decline in average market prices, with the result that buyers can access more affordable live animals. Overall, our paper demonstrates that addressing economic losses offers a more impactful perspective than focusing solely on the more commonly emphasized physical losses.

This paper is organized as follows. Section 2 reviews the literature discussing the issues and challenges faced by people living shock-prone dryland areas. It analyses the relevance of the optimal loss approach by emphasising the effect of multifaceted exogenous shocks on producer market behaviours. Section 3 describes the economic loss model to the Senegalese Sahelian agropastoral production system. Section 4 describes the study area and data used in our analysis. Section 5 presents the main results of the optimization, identifying optimal quantity and price in different loss reduction scenarios. Section 6 discusses the main results and concludes.

2. LITERATURE REVIEW

There are many definitions of food loss, from the more operational (Bourne, 1977; Parfitt et al., 2010; Hodges et al., 2011; FAO, 2011, 2013; Aramyan and van Gogh, 2014; de Gorter, 2014) to the more comprehensive (Papargyropoulou et al., 2014). Food loss occurs at the production, pre-harvest, harvest and post-harvest stages (Parfitt et al., 2010). Food waste refers to the unconsumed portion that is discarded as waste at any point in the food chain (Hodges et al., 2011).

Although food loss and waste, especially the location and type of loss, have been discussed, loss has received relatively little attention due to the difficulties of measurement. Several attempts have been made to estimate loss, particularly in the grain and crop sectors. Early estimates, which used mass flow models, set loss and waste at one-third of the physical mass of all foodstuffs worldwide (FAO, 2013; Lipinski et al., 2013). The World Bank (2011) reported the yearly grain loss in sub-Saharan Africa as approximately US$4 billion. Highlighting these issues is helpful for donors and funding agencies. However, these global estimates have increasingly been challenged, especially in Sub-Saharan Africa, where recent scientific studies have found the magnitude of the loss to be overestimated. More recent estimates have ranged from 4% in the presence of prevention mechanisms to 20% in their absence (Affognon et al., 2015; Rosegrant et al., 2015).

In 2012, the FAO estimated milk loss in the sub-Saharan African dairy sector at 27%; this was found to occur mainly in the early or middle parts of the food chain. However, extensive fieldwork conducted by a CIRAD–Pastoralisme et zones sèches (Pastoralism and dry lands; PPZS) team in 2016 to evaluate loss in the Senegal and Burkina Faso dairy supply chain, valued total milk loss at 4% to 14%, which was very different from the FAO estimate. The potential for recycling and reusing food that is diverted from human consumption to animal consumption has led to the adoption of a more inclusive definition of food loss and waste, which considers both humans and animals in its calculations (Mokkar, 2017).

A key challenge is that the methodological approaches, which were designed and initially applied in developing countries, have relied on the experiences of those countries (Sheahan and Barrett, 2016). In 2009, the European Union tried to support Sub-Saharan African countries by implementing the African Postharvest Losses Information System (APHLIS). This involved a network of local experts and facilitated the collection and sharing of cereal grain weight loss data by country and province (Hodges et al., 2010; Rembold et al., 2011). However, this attempt took place in an oversimplified post-harvest loss environment and there were challenges with data quality (Affognon et al., 2015).

At the micro level, cross-country surveys of farmers in relation to post-harvest loss in Sub-Saharan Africa have revealed interesting findings, with relatively low loss indicators, ranging from 1.4% to 6.9% of total production (Kaminski and Christiaensen, 2014; Abdoulaye et al., 2015). Although designed for large samples, these surveys cannot be readily generalized to the national level because this was not built into their design.

From a value chain perspective, and regardless of variations in magnitude, grain and cereal loss seems to occur more frequently during handling and storage in the on-farm phase. In contrast, fresh product loss is reported to occur more often in the processing and distribution phases. From a technical perspective, this consensus on loss distribution from farm to fork can be explained by the fact that most surveys have addressed on-farm storage loss (Affognon et al., 2015). Current trends and projections for food value chains challenge traditional methodological approaches to integrate chain modifications arising from urbanization and other modern drivers. However, these approaches do provide powerful analytical tools for describing complex interactions between physical and social systems and for enhancing well-being through the reduction of loss in the primary sector. New insights into food loss and waste estimates, particularly in the livestock sector, could contribute to a converging research agenda on the challenges presented by the stress of global, social and environmental change.

Optimising the management of scarce resources, possibly through the minimization of constraints, is a critical theme in economics. Optimisation relies on economic rationality, a fundamental economic principle that guides the decision-making of actors. However, the inclusion of uncertainty leads to the choice of a specific analytical structure that cannot be appropriately represented by the usual constrained optimisation model (Arrow, 1971; Machina, 1987; Kreps, 1988; Dixit, 1990). Moreover, it is well established that behavioural choice may be more fundamental than the rational pursuit of self-interested goals (Bossert and Suzumura, 2012). A flexible approach to rationality-based optimisation facilitates a paradigm shift to a form of bounded rationality (with limited information, cognition and decision-making time), as articulated in Herbert Simon's (1955) seminal work. This also relaxes the constraint that links optimisation to instrumental rationality (Mongin, 2000). In this study, both approaches were considered to reconcile the Sahelian pastoralists' bounded rationality, context-driven behaviours and optimisation processes under conditions of uncertainty.

Risks are a central part of life for most households, especially those in low-income countries (Banerjee and Duflo, 2011). An increased understanding of the risks and the associated coping strategies is key for policy-makers. The main challenge in risk analysis is that the presence or perception of risk can significantly affect the intertemporal behaviours of households in their allocation of resources. This applies not only to poor households but also to non-poor households that have a higher probability of becoming poor in a less safe environment. In developing countries, hazards are ubiquitous in the lives of most farmers, who must secure their livelihoods and minimize their loss. Those with weak assets are usually pushed to engage in low-return and sometimes risky non-farming activities (Barrett et al., 2001), while those who have better financial support, or who are living in regions with favourable alternatives, tend to focus on revenue growth and wealth accumulation (Loison, 2016).

Pastoralists live and operate in shock-prone environments (Wane et al., 2010) in which climate variability plays a central role. This has a direct impact on natural resource dynamics, as herders must deal with spatiotemporal variations. Climate change has exacerbated economic, social, cultural and political unease (e.g., national and international food and feed price volatility, disease, political instability and social transformation). Pastoralists also face market uncertainty and a lack of infrastructure, both of which severely affect their livelihoods. They adapt to these conditions by using mobility and diversification strategies to enhance production and secure their livelihoods (Alary et al., 2015). Their choices are limited by complex relationships and by the multifunctionality of their livestock assets. Some pastoralists breed livestock species with short life cycles to make quick gains and to escape poverty (Alary et al., 2015). Others prefer large ruminants that represent long-term capital investments (Wane et al., 2020).

It should be noted that in a risky environment, holding animals beyond an optimal market period corresponds to a form of contingency rationality. Imperfect and incomplete market information encourages pastoralists to adopt a prudent position that is based on their circumstances and is therefore contingent on the socioeconomic environment (Wane et al., 2009). This explains their opposition to regular animal 'destocking,' even when it is encouraged by national technical support services. Far from being indifferent to market prices (Kerven, 1992), livestock farmers make trade-offs between short-term consumption needs and long-term herd-building strategies to meet future needs (Fadiga, 2013).

With varying levels of success, pastoral and agropastoral households have developed adaptation and coping strategies that reflect a range of responses to stress. This illustrates the close relationship between social and biophysical factors. Extensive pastoral and agropastoral systems cannot be measured purely in terms of assets because they continually evolve and adapt to accommodate their increasingly uncertain biophysical environment and monetized world (Chambers, 1989; Van Dijk, 1997; Bovin, 2000; Ancey et al., 2009).

Over time, smallholders in the Sahelian livestock system have tried to secure production and their livelihoods by considering the uncertainties and disequilibrium of their environment (Benkhe and Scoones, 1983; Wane et al., 2010). Studies on inequality (Sen, 1982; Sutter, 1987; Wane et al., 2009; Mulder et al., 2010) and on the vulnerability of pastoral populations (Swift, 1989; Ancey et al., 2009) have discussed the complexity of the farmers' securitization. The importance of the social and biophysical factors embedded in extensive African crop–livestock systems must be considered. Given these uncertainties, Sahelian farmers are opportunistic in their approach to the markets for goods and services. Market fundamentals are not the primary drivers; rather, cultural, social and non-commercial factors often play a more significant role in producers' selling decisions. These behaviours are so deeply rooted in market practices that two key concepts are critical in any discussion of the issues affecting post-production loss in Sahel ruminant farming.

A key question that needs to be examined is whether complete loss eradication along the agricultural value chain is a feasible option or is loss reduction through optimisation more realistic? Regardless of the level of adoption of technologies, innovations and institutional arrangements, it is reasonable to assume that the cost of eliminating all loss in agricultural value chains would be prohibitive. Accepting that a certain level of failure and loss will inevitably arise in a risky environment is economically rational, because some contamination or spoilage is inevitable (de Gorter 2014). Assuming that a certain amount of loss in agricultural value chains is necessary and even economically rational, the focus should be on improving the microeconomic behaviours underpinning the potential sources of loss before developing strategies to mitigate the effects of individual decisions (Waterfield and Zilberman, 2012; Horton and Hoddinott, 2014; de Gorter, 2014; Goldsmith et al., 2015; Sheahan and Barrett, 2016). Losses may also arise from the voluntary and intentional decisions of economic actors, particularly those focused on profit rather than production maximization. Brazilian soybean farmers exemplify this situation (Goldsmith et al., 2015). In terms of food safety, it is also possible that loss may be desirable when unsafe food is removed from the system to avoid human or animal contamination (Magoha et al., 2014). In a dynamic analysis, the management of farm loss could yield mixed results. For example, by expecting losses due to a lack of storage facilities, farmers could be forced to sell products at lower price. In this case, quantitative loss could be low, while value-related loss would be very high, as was the case for maize farmers in Benin (Kodjo et al., 2015). Because zero loss is likely to be an unattainable ideal, especially for Sub-Saharan livestock farming, an optimal loss approach would be more appropriate.

Identifying the main loss sources and estimating the amount of loss is only a starting point of the analysis. In fact, a major difficulty is the choice of counterfactuals against which the loss is to be measured. Naturally, these counterfactuals are related to the production system. Producers hold the females and sell the steers in an extensive production system. The useful life of a Zebu cow is 4.5 to 8.5 years, during which time parturition, including abortion, occurs approximately five times (Mukassa-Mugerwa, 1989). Following production, live animals are moved along the value chain to downstream markets for final use, and loss occurs at each stage. For livestock systems, especially those in Sub-Saharan Africa, this is the central theme of a debate that does not occur in crop systems.

'Postproduction loss' and 'postharvest loss' have been used interchangeably to reflect specific problems in the agricultural sector. These concepts, which refer to the temporal dimension, are equally relevant to studies on the livestock sector or to specific products, which may be perishable (e.g., meat, milk) or non-perishable (e.g. cereals). Bourne (1977) made an operational distinction based on three periods during which food loss occurs: 'pre-harvest,' 'harvest,' and 'post-harvest'. This classification allows for harvest and post-harvest losses to be combined into a single category: post-production loss. Thus, combining pre-market and market losses to focus on post-production loss would appear more relevant. Recent definitions of food loss integrate the whole process, including food grown to maturity but not harvested and left in the field for any reason (Minor et al., 2020).

3. MODELLING ECONOMIC LOSS IN SAHELIAN ANIMAL PRODUCTION SYSTEMS

Two distinct phases of economic loss in live-animal rearing should be considered. The first is the pre-market phase, in which animal mortality, theft and disappearance occur. This type of loss is related mainly to the costs of managing animals prior to their theft or death. In other words, the farmer loses the entire investment made in such animals. The second is the market phase, which starts with the decision to sell the animal and ends with the actual sale. Two types of loss can occur at this stage: (i) death or disappearance at the mark-to-market stage or (ii) loss of profits or opportunity costs at sale. This second stage could be summarized as follows: what would have been earned if the farmer had sold the animal at the ideal age vs. what would have been earned if the animal had been sold earlier (for animals above the ideal age). Optimisation would involve the sale of animals that are close to the ideal age at a good price while maintaining the herd structure. In other words, it involves the minimization of economic loss in the production of live animals. Finally, there are various stages at which loss is calculated in both the pre-market and market phases. This leads to a global loss function as follows:

$$f(x_i^{as}, P_i^{as}) = \sum_{as \in AS} \Big[\left(P_{M_1}^{as} - \bar{C}^{as} * A_{M_1}^{as}\right) * M_{PM}^{as} + \left(P_{V_1}^{as} - \bar{C}^{as} * A_{V_1}^{as}\right) * V_{PM}^{as} + \left(P_{\Delta_1}^{as} - \bar{C}^{as} * A_{\Delta_1}^{as}\right) * \Delta_{PM}^{as} + \left(P_{M_2}^{as} - \bar{C}^{as} * A_{M_2}^{as}\right) * M_{MP}^{as} + \left(P_{V_2}^{as} - \bar{C}^{as} * A_{V_2}^{as}\right) * V_{MP}^{as} + \left(P_{\Delta_2}^{as} - \bar{C}^{as} * A_{\Delta_2}^{as}\right) * \Delta_{MP}^{as} + \left[\sum_{i<\bar{A}^{as}} (\bar{P}^{as} - P_i^{as}) x_i^{as} - \bar{C}^{as} x_i^{as} (\bar{A}^{as} - i)\right) + \sum_{i=\bar{A}^{as}}^{A^{as}} (\bar{P}^{as} - P_i^{as}) x_i^{as} + \bar{C}^{as} x_i^{as} (i - \bar{A}^{as})\big)\Big]\Big] \quad (1)$$

where x_i^{as} = number of animals sold at age i by species, P_i^{as} = sale price of animals at age i by species, A^{as} = ideal age for sale according to livestock keepers, $P_{M_1}^{as}$ = cost of dead animals during the pre-market phase, $P_{V_1}^{as}$ = cost of stolen animals during the pre-market phase, $A_{M_1}^{as}$ = age of dead animals during the pre-market phase, $A_{V_1}^{as}$ = age of stolen animals during the pre-market phase, $P_{M_2}^{as}$ = cost of dead animals during the market phase, $P_{V_2}^{as}$ = cost of stolen animals during the market phase, $A_{M_2}^{as}$ = age of dead animals during the market phase, $A_{V_2}^{as}$ = age of stolen animals during the market phase, $\bar{P}^{as}$ = average price of animals at ideal age at sale, C^{as} = average cost of managing an animal by species, M_{PM}^{as} = number of animal deaths during the pre-market phase, V_{PM}^{as} = number of animals stolen during the pre-market phase, Δ_{PM}^{as} = other animals lost during the pre-market phase, M_{MP}^{as} = number of animal deaths during the market phase, V_{MP}^{as} = number of animals stolen during the market phase, Δ_{MP}^{as} = other animals lost during the market phase.

Optimisation process and numerical resolution

For the numerical resolution of the loss function, two strong assumptions were made:

- *Assumption 1*: Stolen, lost or dead animals in the pre-market phase would have reached the ideal age at sale.
- *Assumption 2*: Most stolen, lost or dead animals in the market phase would have reached the ideal age at sale.

Thus, equation (1) can be rewritten as follows:

$$f(x_i^{as}, P_i^{as}) = \sum_{as\in AS}\Big[(\bar{P}^{as} - \bar{C}^{as} * \bar{A}^{as}) * \ [(M_{PM}^{as} + M_{MP}^{as}) + (V_{PM}^{as} + V_{MP}^{as}) + (\Delta_{PM}^{as} + \Delta_{MP}^{as})] + \big[\sum_{i<\bar{A}^{as}}\big(\bar{P}^{as} - P_i^{as})x_i^{as} - \bar{C}^{as}x_i^{as}(\bar{A}^{as} - i)\big) + \sum_{i=\bar{A}^{as}}^{A^{as}}(\bar{P}^{as} - P_i^{as})x_i^{as} + \bar{C}^{as}x_i^{as}(i - \bar{A}^{as}))\big]\Big]$$

where x_i^{as} = number of animals sold at age i by species, P_i^{as} = sale price of animals at age i by species, $\bar{A}^{as}$ = ideal age for sale according to livestock keepers, P^{as} = average price of animals at ideal age at sale, $\bar{C}^{as}$ = average cost of managing animals by species, M_{PM}^{as} = number of animal deaths during the pre-market phase, V_{PM}^{as} = number of animals stolen during the pre-market phase, Δ_{PM}^{as} = other animals lost during the pre-market phase, M_{MP}^{as} = number of animal deaths during the market phase, V_{MP}^{as} = number of animals stolen during the market phase, Δ_{MP}^{as} = other animals lost during the market phase.

The optimal loss approach is meant to minimize the loss function subject to constraints by considering $P=(P_i^{as})=(P_j)_{1\leq j\leq n}$ and $X=(x_i^{as})=(X_j)_{1\leq j\leq n}$ vectors corresponding to the unit price and the number sold, respectively, by species, season and age; with $n=\sum_{as\in AS}A^{as}$; where A^{as} is the maximum age reached by animal species on a family farm.

Definition of constraints in the optimisation programme

The minimization of the post-production loss function was performed on variables P_i^{as} and x_i^{as}. Because of the nature of these variables, P_i^{as} and x_i^{as} were positive $\forall i\in\{1,\ldots,A\}$ and $\forall as\in$AS . This paper distinguishes between the main and complementary constraints to facilitate the resolution of the optimisation problem.

The main constraint is based on the overall income constraint: the sum of the farmer's annual sales is sufficient to cover all the total consumer expenditures (food and non-food) made by the farmer, leaving a profit margin that is at most equal to a share a of total expenditures.

$$\textit{Total expenditures } D\leq \sum_{as\in AS}\sum_{i=1}^{A^{as}} P_i^{as}(s)x_i^{as}(s) \ \leq a^{*}\textit{total expenditures}$$

This constraint can be written as follows: $D\leq\sum_{j=1}^{n}P_jX_j\leq a^{*}D$

Additional constraints are defined on critical parameters, such as the loss function, prices and number of animals.

Constraint on the loss function

The mathematical function for defining the loss function can be negative for some parameters. Therefore, it is important to constrain it to a positive value. The constraint is defined as follows: $f(x_i^{as}, P_i^{as})\geq 0$.

Constraints on prices

Several constraints on prices were considered to avoid price outliers.

- *Constraint 1*: The vector P^0 is a system data point obtained from the database. Without harming generality, vector P^0 is equal to the vector of the ideal selling prices, which are informed by each farmer for a species at the favourable age at sale. This constraint is defined as follows:
  $P=(P_1,P_2,\ldots,P_n)\leq P^0=(P_1^0, P_2^0,\ldots,P_n^0)$
- *Constraint 2*: This stipulates that the sale price of a species at age i must be greater than the cost of the animal incurred from birth (the average age at which the animal entered the farm) to the age at which it is sold. This translates into the following:
  $P \geq CU \Leftrightarrow P_j \geq CU_j, \forall\, j \in \{1, \ldots, n\}$
  $\Leftrightarrow P_i^{as} \ \geq CU_i^{as}, \forall i \in \ \{1, \ldots, A\}\ et\ \forall as \in AS$
  with $CU = (CU_j)_{1\leq j\leq n} = (CU_i^{as})$ with $CU_i^{as} = \bar{C}^{as} * i$
- *Constraint 3*: The selling price curves for each species are concave functions of age. Thus, prices increase with age until they reach their maximum at the ideal age, then they decrease. This can be expressed as follows: $P_1^{as}\leq\cdots\leq P_{\bar{A}^{as}}^{as}\geq P_{\bar{A}^{as}+1}^{as}\geq\cdots\geq P_{A^{as}}^{as}$.

Constraints 2 and 3 will cause some prices to be higher than they would have been before the ideal age (see all) because the producer would have spent more on an older animal than on a younger one. This result is unlikely in the case of female cattle because they are more expensive when younger (up to a certain age) due to their milk production capacity. Therefore, for female cattle, the fact that the price of cattle older than 10 years is lower than the price of those three years old is added to the previous constraint. For female cattle, the constraint is presented as follows:

$P_1^{as} \leq P_2^{as} \leq P_{A^{as}}^{as} \leq \cdots \leq P_{\bar{A}^{as}+1}^{as} \leq P_3^{as} \leq \cdots \leq P_{\bar{A}^{as}}^{as}$.

Constraints on the number of animal species sold

- *Constraint 4*: This is based on the animal off-take rate. A previously explained, farmers in pastoral and agropastoral systems will sell a limited number of animals just to meet their needs. The herd off-take rate is relatively constant. This constraint stipulates that the total number of animals (of any species at any age) sold is, at the most, equal to the herd off-take rate. It is defined as follows:

$$\sum_{as \in AS} \sum_{i=1}^{A} x_i^{as} = \sum_{j=1}^{n} X_j \leq \textit{off-take rate} * \textit{herd size}$$

- *Constraint 5*: There is a hierarchy in the pastoral and agropastoral species that are sold. Small ruminants are more likely to be sold than cattle, which are the main assets of livestock producers. The constraint therefore stipulates that the total number of cattle sold is lower than the total number of small ruminants sold.

For the remainder of the paper, the following group of constraints is considered: $Ens_{cont}1$={(X,P) that meet constraints 1,2,3,4 and 5}.

Formulation of the optimisation problem

Without any intervention, the number of dead, stolen or lost animals is given for the farmer who is unable to minimize this loss. Quantity loss (by theft, death and disappearance) during the premarket and market phases should be considered as a constant in the minimization problem. Therefore, the following is posed:

$$G = \sum_{as \in AS} (\bar{P}^{as} - \bar{C}^{as} * \bar{A}^{as}) * [(M_{PM}^{as} + M_{MP}^{as}) + (V_{PM}^{as} + V_{MP}^{as}) + (\Delta_{PM}^{as} + \Delta_{MP}^{as})]$$

subject to:

$$(\mathrm{P}): \begin{cases} \min f(X,P) \\ sc \\ D \leq \sum_{i=1}^{n} P_i X_i \leq a * D \\ f(X,P) \geq 0 \\ (X,P) \in \ Ens\_cont1 \\ X_i \ \geq 0, \forall i \\ P_i \ \geq 0, \forall i \end{cases}$$

with $f(X,P)=Losses_{Value}(X^{as},P^{as})+G$.

Solution for the optimisation model: convexity or concavity of the loss function

The nature of the loss function can be analysed in its matrix form.

$$f(X,P) = G + \sum_{as \in AS}\left[\sum_{i<\bar{A}^{as}}\left(\bar{P}^{as} - P_i^{as}\right)x_i^{as} - \bar{C}^{as}x_i^{as}(\bar{A}^{as} - i)\right) + \sum_{i=\bar{A}^{as}}^{A^{as}}(\bar{P}^{as} - P_i^{as})x_i^{as} + \bar{C}^{as}x_i^{as}(i - \bar{A}^{as}))\right]$$

thus, $f(X,P) = \sum_{as \in AS} \sum_{i=1}^{A^{as}} (\bar{P}^{as} - \bar{C}^{as}|\bar{A}^{as} - i|)x_i^{as}(s) - \sum_{as \in AS} \sum_{i=1}^{A^{as}} P_i^{as}(s) x_i^{as}(s) + G$

by posing $B_i^{as} \bar{P}^{as} - \bar{C}^{as}|\bar{A}^{as} - i|$; therefore:

$$f(X,P) = \sum_{j=1}^{n} B_j X_j - \sum_{j=1}^{n} P_j X_j + G$$

where $B = (B_i^{as}) = \left(B_j\right)_{1 \leq j \leq n}$ $P = (P_i^{as}) = \left(P_j\right)_{1 \leq j \leq n}$, $X =$, $(x_i^{as}) = \left(X_j\right)_{1 \leq j \leq n}$.

With the same calculations at the constraint level, the problem (P) becomes:

$$(P1): \begin{cases} \min f(X,P) = (B-P)'.X + G \\ sc \\ D \leq P'.X \leq a * D \\ f(X,P) \geq 0 \\ (X,P) \in \ Ens\_cont1 \\ X_j \ \geq 0, \forall j \\ P_j \ \geq 0, \forall j \end{cases}$$

Starting with the minimization problem ($P1$), the unknowns in this minimization system are the vectors P and X.

$$f(X,P)=(B-P)'.X+G=\sum_{i=1}^{n} B_i X_i - \sum_{i=1}^{n} P_i X_i + G$$

The Hessian matrix of the function $f(X,P)$ is given by:

$$H(X,P) = \begin{pmatrix} \frac{\partial f(X,P)}{\partial x_1 \partial x_1} & \cdots & \frac{\partial f(X,P)}{\partial p_n \partial x_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial f(X,P)}{\partial x_1 \partial p_n} & \cdots & \frac{\partial f(X,P)}{\partial p_n \partial p_n} \end{pmatrix}$$

Thus,

$$H(x^{as}, P^{as}) = -\begin{pmatrix} 0 & \dots & 0 & 1 & 0 & 0 \\ \vdots & \ddots & \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & \vdots & 0 & 1 \\ 1 & 0 & \vdots & \ddots & \dots & 0 \\ 0 & \ddots & 0 & \vdots & \ddots & \vdots \\ \vdots & 0 & 1 & 0 & \dots & 0 \end{pmatrix}$$

with $\frac{\partial f(x,y)}{\partial x_i \partial p_i} = \frac{\partial f(x,y)}{\partial p_i \partial x_i} = -1$.

The following is considered:

$$M = \begin{pmatrix} 0 & \dots & 0 & 1 & 0 & 0 \\ \vdots & \ddots & \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & \vdots & 0 & 1 \\ 1 & 0 & \vdots & \ddots & \dots & 0 \\ 0 & \ddots & 0 & \vdots & \ddots & \vdots \\ \vdots & 0 & 1 & 0 & \dots & 0 \end{pmatrix} = -H$$

However, $det(M)=1>0$ means that M is positive, and H is negative; thus, the loss function $f(X,P)$ is concave. The concavity of the function $f(X,P)0$ makes conventional methods inadequate for achieving the loss minimization objective. Therefore, a non-linear programming approach, the method of moving asymptotes (MMA), was used. This numerical resolution method, which belongs to the family of convex approximation methods, is suitable for structural optimisation problems. The MMA provides the best results for concave minimization problems.

4. DATA

A mixed approach to data collection was used to answer the research questions about economic loss. Qualitative and quantitative data were sequentially collected in northern Senegal pastoral and agropastoral areas (Ferlo region).

The area of Ferlo is 67,610 km^2, nearly one-third of the country. The climate is characterized by rainfall concentrated over two to three months. The annual average is less than 200 mm in the extreme north and more than 550 mm in the south.

In the vast area of Ferlo, the selection of sites for the study was based on a previous study by Wane et al. (2007, 2009, 2010) who had distinguished one agropastoral area (Thiel) and two pastoral sites (Tatki and Rewane) on a North-South gradient for their representativeness of the ecological, geographical, pastoral and biological diversity of the extensive production system of Senegal (see, their socioecological characteristics in Appendix 1). The data collection tools, administered in July and August 2016, addressed the 2015 rainy season[1] through until early 2016 rainy season.

The study focused on a sample of 202 encampments out of 389 potential encampments, for which complete data on the pastoral households was obtained. There was an error margin of 4.79%, with a confidence interval of 95%, thus keeping within standard statistical norms.

Focus groups were conducted at each of these three locations in November 2015. The composition of the focus groups was as follows: 14 participants (14 men) in Tatki; 14 participants (13 men and 1 woman, who did not participate in the discussion) in Rewane; and 14 participants (13 men, including the sub-county chief and 1 woman) in Thiel. The main information collected from these group discussions related to household income-generating activities and animal species traded in the production area, livestock loss in the production area and seasonal loss.

Additional primary data[2] were gathered from responses given by 202 livestock farmers raising small ruminants and/or cattle – 40% from Thiel, 31% from Tatki and 29% from Rewane – to a detailed questionnaire.

[1] Two distinct seasons characterize Senegal's climate: a dry season from roughly October to May and a rainy season from June to September. While the arid zones receive a total rainfall of under 300 millimetres per year, the forested south receives an average of 1200 mm/year. Rainfall is highly variable, both on the interannual and inter-decadal timescales. The average annual temperature for Senegal was 27.8°C for the period 1960–1990, with monthly averages in the hottest seasons of up to 35°C. (https://climateknowledgeportal.worldbank.org/country/senegal/climate-data-historical)

[2] The following data were collected from household investigations: pastoral encampment location, household socio-demographics, herd species composition, ideal average age and selling prices by species and sex, sales decision-making, number of pastoral sub-seasons, average sales volume and prices by species and sub-season, sales motivations, sub-season sales locations, mortality-related quantitative loss, theft and loss, risk hierarchy by species, average animal weight loss during transport to market, herd maintenance and transportation expenses, and the hierarchy of strategies dealing with shocks. The questionnaire ended with a question on the worst rainy season in the previous decade. Pastoral encampments are identifiable socioeconomic settlement units that reveal an aggregate income. They can involve one or more households, which are defined as nuclear or relational units of married couples or blood relatives.

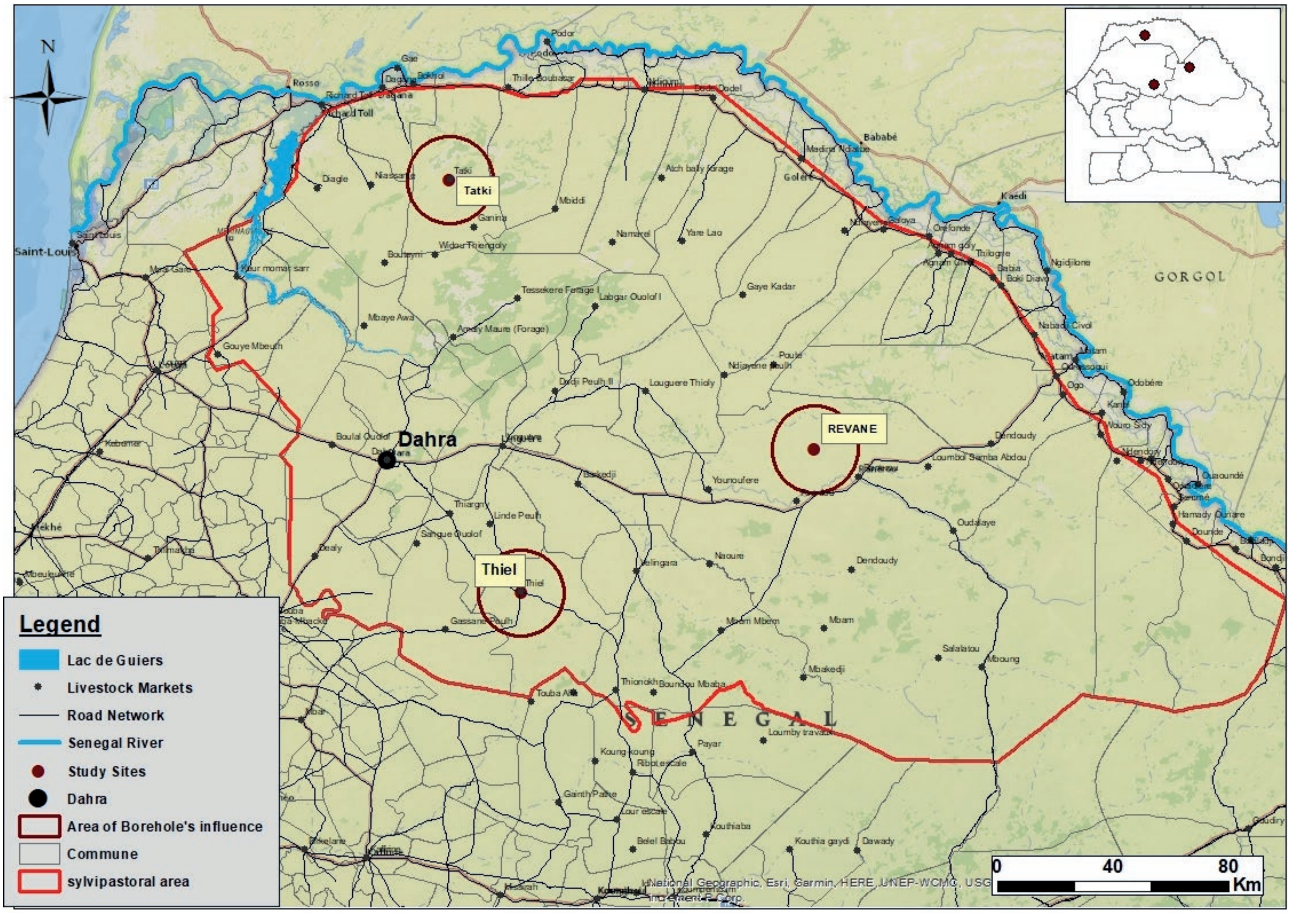

Figure 1. Map of the study location.

5. RESULTS

The results of the optimisation model, which was applied to 202 agropastoral encampments, focussed on a combination of sales volume and selling price by age and species. These data should make it possible for average livestock farmers to minimize their economic loss by generating income to cover their expenditures.

Sales volume

To minimize their economic loss, the average farmer would have to sell 4% male cattle, 26% female cattle, 22% male sheep, 13% female sheep, 17% male goats and 16% female goats from their herd annually (Table 1). The same trends have been observed in other pastoral and agropastoral production systems. Because of the multiple non-commercial roles of cattle in the lives of pastoral producers, cows are not primarily for sale. In uncertain environments, pastoralists always try to maximize the non-monetary benefits from their cattle, despite the long-term costs of raising the animals. Therefore, loss minimization would require the increased application of these strategies to the more effective marketing of cows.

Ideal age at sale

The distribution of optimal sales by species and area shows that the 4% male cattle sales should consist of 58% bulls at an average age of 5 to 6 years (Figure 2). Spatial differences are related to differences in the production systems. Loss optimisation follows the climatic gradient because the bulls sold must be approximately 5 to 6 years old. The data showed that 77% of male cattle are sold in Tatki, the driest zone; 54% in Rewane, the intermediate zone; and 41% in Thiel, the wetter zone.

The situation is slightly different for female cattle. In the study area as a whole, the optimal combination of 92% of sales should comprise cows at an average age of three to five years. The optimal sales volume of cows

Table 1. Approximate distribution of retained animals and optimum number for sale by species and area.

		Rewane (%)		Tatki (%)		Thiel (%)		Survey area (%)	
		Retained	Sold	Retained	Sold	Retained	Sold	Retained	Sold
Cattle	Male	7	8	4	4	2	3	4	4
	Female	18	25	21	27	15	27	18	26
Sheep	Male	14	25	13	22	7	21	11	22
	Female	41	10	47	13	54	16	49	13
Goat	Male	2	19	3	18	3	14	3	17
	Female	18	12	12	17	18	18	16	16

of three to five years old decreases from the wettest area around Thiel (92%) to the intermediate area around Rewane (91%) to the dry area around Tatki (90%).

Regarding small ruminants, a very large number of male sheep are sold during the Tabaski festival. Tabaski, or Eid ul Adha [the Feast of Sacrifice], is a religious festival and the most important feast in the Muslim calendar, requiring the sacrifice of rams. This suggests that optimal sales (49% of the herd) would be rams at the average age of two, three or even four years.

Female sheep and male and female goats play a role in short-term cash flow. The optimal sales are almost equally distributed across all ages, beginning with the first year, which is devoted to animal fattening. The animals sold are mainly male sheep (36% of herd) and female sheep (32%) aged two to three years. For goats, the target composition is males aged two to four years (48% of herd) and females aged five to six years (29%).

Ideal price at sale

The unit price of an animal is a concave function of its age. The optimal model would be for the farmer to sell male cattle at seven years of age at an average price of 271,000 XOF (Figure 3). Before this ideal age,

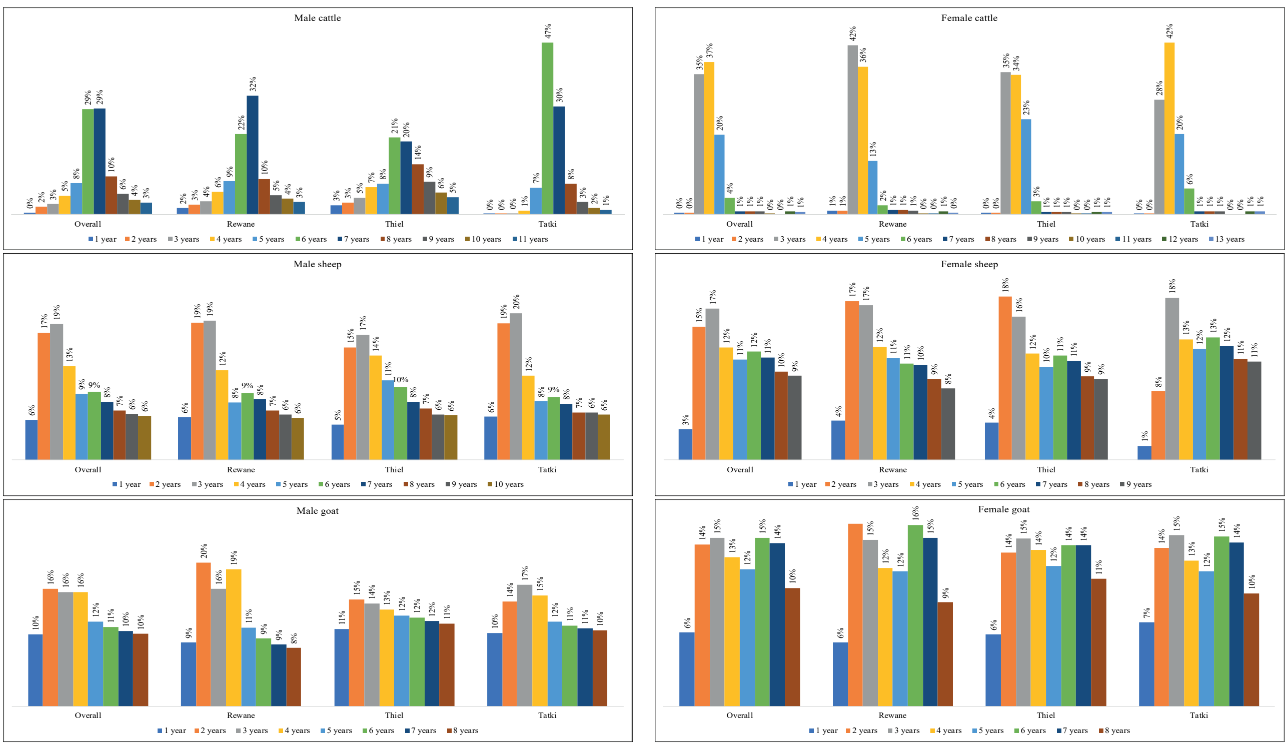

Figure 2. Optimal number of animals for sale by age, species and area.

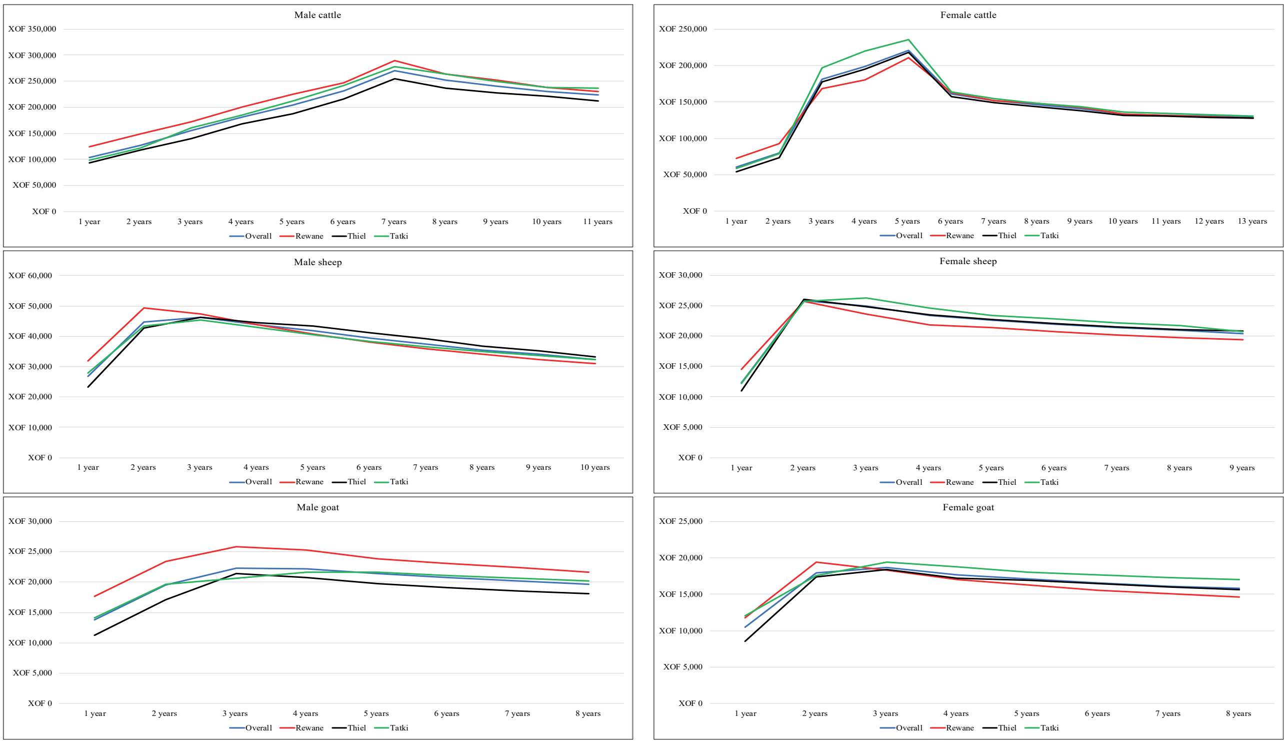

Figure 3. Optimal selling price of animals by species and area.

the average price rises and then falls, while remaining close to the price level for the five- to seven-year-old cattle. For female cattle, the model shows that the ideal age at sale would be reduced to five years (the farmers had initially indicated eight years) for a maximum unit gain at the optimum price of 221,000 XOF. The trajectories of the price curves were similar to those observed for the male cattle. The prices for male cattle tended to be higher in Rewane and Tatki, which are the more isolated areas in the more arid northern region.

For sheep, the ideal age at sale is approximately two years for both males and females. The difference lies in the optimum price, which would be 49,000 XOF for males and roughly half, at 26,000 XOF, for females. The average annual prices for male sheep are relatively high, particularly during Eid ul Adha, which is celebrated by the dominant community (nearly 94% of the population) in Senegal. As with cattle, male sheep have a higher value in Rewane.

For goats, the average ideal age at sale is zone-dependent. In Rewane and Thiel, breeders must sell their male goats at approximately three years of age for an average of 21,000–26,000 XOF. In Tatki, breeders must wait five years to realise an average of 22,000 XOF. For females, there is less variation by area. If the Rewane and Thiel breeders can sell their two-year-old female goats for an average of 17,000–19,000 XOF, the Tatki breeders will realise 19,000 XOF for three-year-old animals.

The optimisation model describes a situation in which the average farmer can minimize physical loss through animal theft and death. This is considered a reference point, or 'business as usual'. Consequently, the study arbitrarily chose three loss reduction scenarios: with a 25%, 50% and 75% reduction in average loss. The effects of these scenarios on the market parameters were then simulated.

Simulation of ad hoc *loss reduction scenarios*

Two radically contrasting periods experienced in Sahelian pastoral areas (including Northern Senegal) were compared: 2014–2015 (period 1), which was characterized by very scarce rainfall in several areas, and 2015–2016 (period 2), characterized by plentiful and evenly distributed rainfall. The comparison showed that losses involving the total herd population on transhumance were 23% in period 1 and 9% in period 2 for cattle; 26% in period 1 and 8% in period 2 for sheep and 43% in period 1 and 11% in period 2 for goats. These figures are far from the 40% to 70% loss rates observed during the droughts of the 1970s and 1980s (Thebaud, 2017). Based

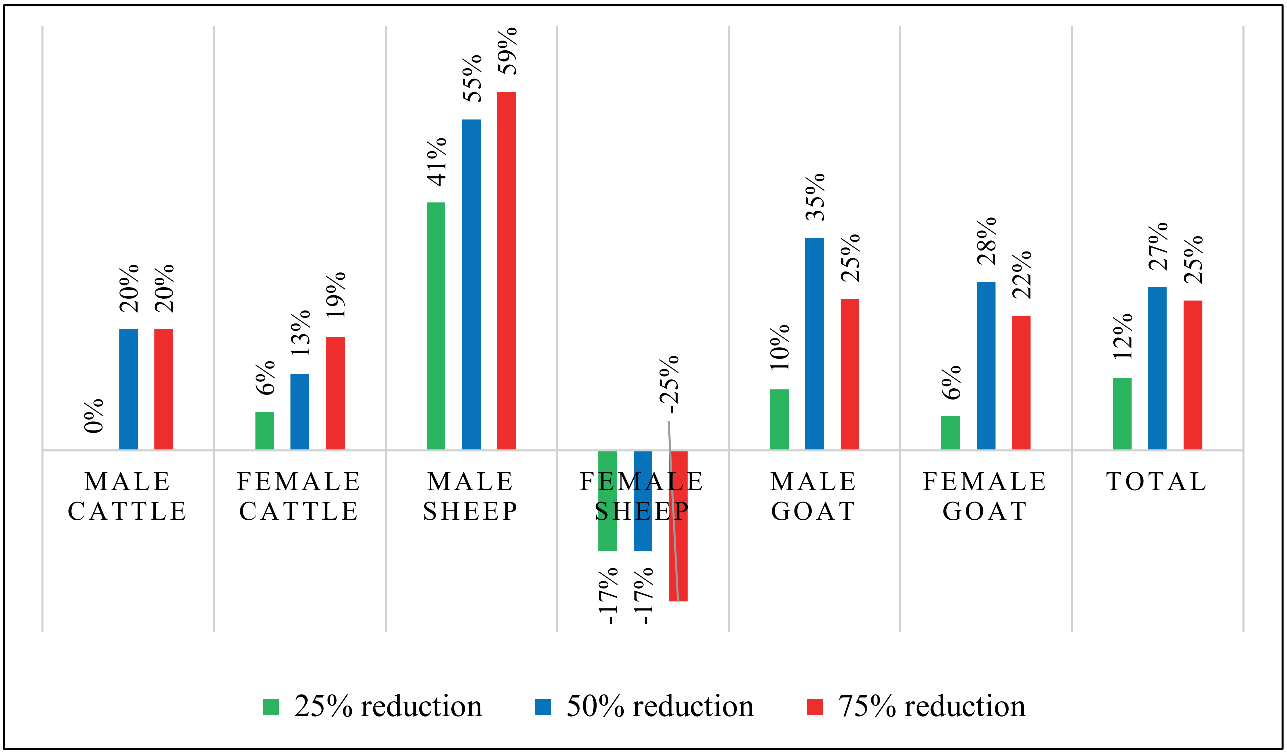

Figure 4. Changes in numbers available for sale with varying loss reduction scenarios.

on this analysis, we developed three ad hoc loss reduction scenarios – 25%, 50%, and 75% – to determine their effects on volume and market price parameters.

Decreases of 25%, 50% and 75% in losses from theft and death would result in increases of 12%, 27% and 25% in the number of cattle, sheep and goats, respectively, available for sale (Figure 4). The exception would be female sheep, for which there would be a 17% to 25% decrease in the number available for sale. The species most sensitive to loss reduction would be male sheep, which, given their market value, particularly during Eid El Adha, are prime targets for theft. Small ruminants are easier to steal and conceal.

The reduction in the loss of female sheep would lead to a decrease in their available number and in the selling price. The relative stability in the number of male cattle available for sale is indicative of the market relationship with this main element of the pastoralist's heritage. First, only 20% would be available for sale following a 50% reduction in loss. For female cattle, the greater the loss reduction, the greater the number available for sale.

All loss reduction scenarios resulted in average market prices generally declining (Figure 5). In the 25% reduction scenario, the smallest negative price change was observed for female cattle, and the largest negative price change was observed for male goats. The 50% reduction scenario allowed for a minimum negative price change of 3% for male cattle and a maximum of 15% for male sheep and female goats. The 75% reduction scenario resulted in a minimum negative price change of 5% for male cattle and a maximum negative price change of 18% for male sheep.

6. CONCLUSION

Given the complexity of loss issues in the ruminant sector, this study identifies several dilemmas presented by the existing analyses of the post-production loss of livestock. These include the zero loss vs. optimal loss approaches. Other issues include the starting point for analysis: pre-market vs. market vs. post-market; enterprise vs. pastoral household model for production systems; intensive vs. semi-intensive vs. extensive; quantitative loss vs. qualitative loss vs. economic value loss; and constraint management vs. risk management.

This study adopted a framework previously tested in the Senegalese livestock production system. It applied a risk approach to analyse the quantitative and economic value of pre-market and market loss in the extensive pro-

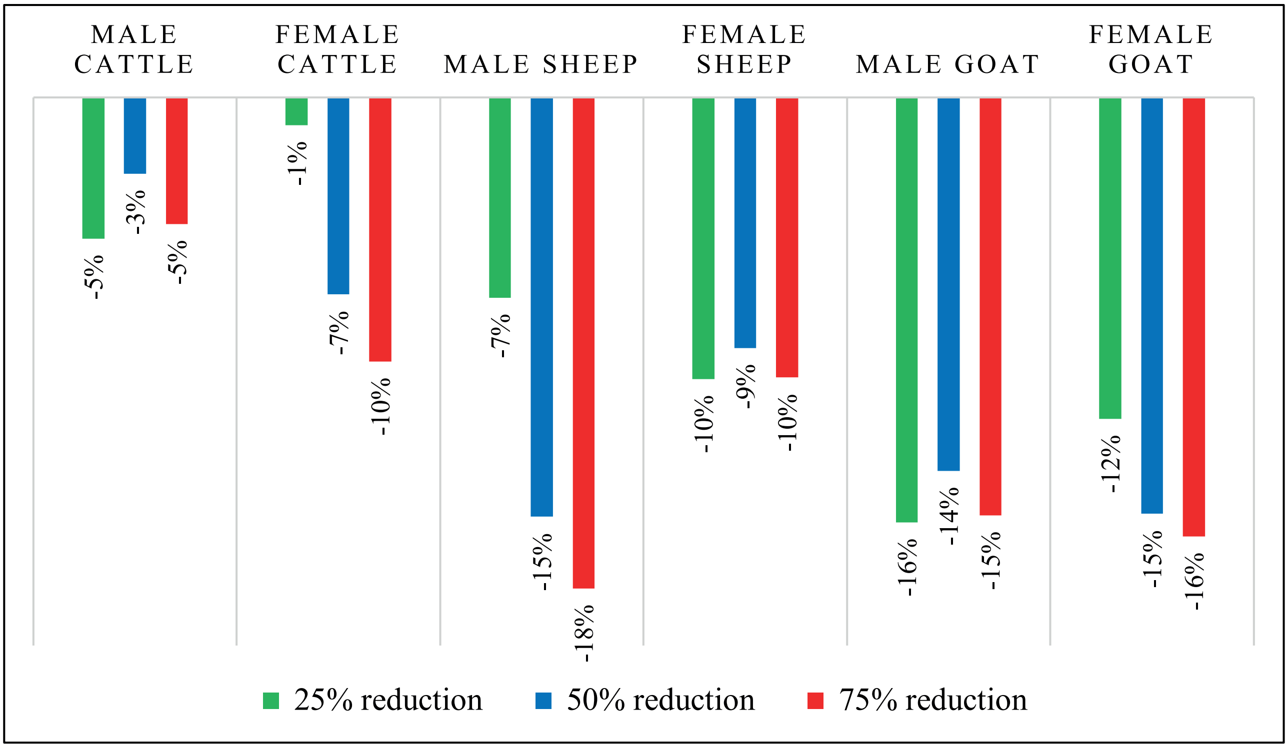

Figure 5. Selling price changes in loss reduction scenarios.

duction systems in Senegal. It elaborated a loss function by summarizing the global monetary loss for big and small ruminants based on the producers' perspectives of the number and prices of animals sold at different ages and sub-seasons. Overall, the study supports the idea of an optimal loss, beyond which further loss reduction is not feasible due to the costs of mitigation. Finally, based on the field data, an empirical exercise was performed to minimize the losses related to animal mortality and theft, subject to the constraints intrinsic to the Sahelian pastoralist. Thus, the effects of the three loss reduction scenarios on market parameters were modelled.

Although intuitive, a new perspective on the value of loss reduction emerged from this study: addressing economic loss is essential. It must be noted that quantitative loss is not necessarily detrimental in the context of general or partial equilibrium because a decrease in food availability can lead to an increase in prices and, thus, in pastoralists' revenues. Therefore, an identification of market fragility and reasoning in terms of opportunity costs or gains allows for a more comprehensive understanding of the economics of pastoralism. However, the simultaneous challenges of food security and improved market parameters (quantities and prices) remain.

The optimisation model also shows that loss reduction can have beneficial effects in relation to the number of animals (except female sheep) available for sale, precipitating a downward trend in market prices. Male sheep were the species most sensitive to loss reduction. All the ad hoc loss reduction scenarios resulted in lowered market prices. Showing the flow of the economy through a social accounting matrix would provide a comprehensive and economy-wide database of the transactions between economic agents during a specific period. In addition, it would be useful for highlighting the importance of loss reduction.

These insights indicate the relevance of loss-reduction policies and actions for addressing food security and competitiveness in the live ruminant sector. Due to the growing complexity and uncertainty in this sector, policies and actions should contribute to the reduction of risk and uncertainty and the prevention of potential conflicts while contributing to growth and resilience. A priority should be the development of a genuine risk culture by providing information on the main risk factors and their occurrence; analysing their economic, social and environmental impact; identifying and evaluating existing risk management tools; and providing guidance on risk prioritisation and management.

In recent years, policies have been developed to create an enabling environment in Senegal. In addition, emerging initiatives address various degrees of severity. However, innovative financial instruments (livestock insurance and credit) and effective information systems could complement the standard approaches to combating disease, animal theft and productivity, as well as the rehabilitation and development of the market infrastructure. As a risk-transfer instrument, the development of livestock insurance could contribute to the reduction of vulnerability by providing compensation against economic loss. Thus, smallholders could avoid using sub-optimal coping strategies that further weaken their precarious food and nutritional status or prevent them from using the limited basic infrastructure (e.g., schools, health centres and markets). In addition, productivity could be improved through revitalized investments.

This paper breaks new ground on economic loss in livestock production systems in the Sahel. Given the multifunctionality of livestock and the objective effects of increasing uncertainty, Sahelian pastoralists have mostly used bounded rationality. Thus, integrating their motivations to sell was key. Therefore, an optimisation model subject to pastoral constraints enables the determination of the optimum number of animal species that must be sold to cover expenditure and animal losses.

DATA AVAILABILITY STATEMENT

The datasets, programmes, a full list of data sources, and information on empirical analysis, experiments and simulations generated for this study are available on request from the corresponding author.

ETHICS STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX 1 – SOCIOECOLOGICAL CHARACTERISTICS OF THE TARGET SITES

Tatki, a sandy area in the northern frontier of Ferlo, is exclusively pastoral. Its proximity to national roads and the Senegal River Valley (40 km away) facilitates trade and social links between farming populations. The communities are scattered around a pastoral borehole built in 1953. There is a basic infrastructure that does not function very well. Health services are provided through the intermittent presence of a health officer. A primary school is located close to the borehole, and there is a weekly livestock market mainly for small ruminants, which are prevalent in the herds. Comprising 60% of the Tatki herds, sheep are the dominant species. Cattle account for 25% and goats for 15% of the herds.

Rewane, in east central Ferlo, is an extensive livestock production area. The infrastructure here is mostly non-functional. There is a health office, a school with only two teachers, and a non-resident extension agent who makes occasional visits from Dahra, which is 82 km away. Almost all residents are animal producers. There is one trader and one transporter. The Rewane herds have the lowest proportion of sheep: 55% sheep (41% female and 14% male), 25% cattle and 20% goats.

Thiel, which is further south in Ferlo's agropastoral area, is inhabited by Fulani livestock keepers and farmers of other ethnic groups. Thiel is an important hosting area for transhumance. The basic infrastructure here functions better than those identified in Tatki and Rewane. Two boreholes were built before 1993. The presence of sedentary family farmers explains the school's relatively good functioning. Thiel's bi-weekly market might result from its proximity to Dahra (40 km away), the country's biggest cattle market.

Following Wane et al.'s (2009) study, different settlement units were targeted. These were first stratified by locality, which indicated the pastoral households' place of physical presence and economic activities. This locality then made it possible to identify both the encampments, concessions and households. The encampments are large units of residence, and because they are directly identifiable settlement units, they revealed the level of market income aggregation that we chose to assess in this study. In addition, there are concessions, socio-economic units in which individuals (possibly blood-related) pool their resources for the common good. Finally, there are households of atomic relational units comprising blood-related or married individuals. The sample was structured according to the density of the geo-referenced encampments. The definitions for the weightings of the encampment categories ('very big,' 'big,' 'middle,' and 'small') were validated by the livestock producers and allowed for weighting according to initial densities. As we obtained various perceptions of these categories, we built ours around the average thresholds.