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Optimizing Antimicrobial Use for Mastitis Control in Dairy Herds: Bioeconomic Trade-Offs and Marginal Abstraction Cost Curves

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ABSTRACT

Preserving udder health remains the main justification for antimicrobial use (AMU) in dairy herds, and adjusting such use is central to minimizing AMU overall. Determining optimal AMU levels and their practical guidelines is complex because AMU is influenced by numerous interrelated factors. To examine the balance between reduced AMU, labor input, and financial outcomes, the bioeconomic stochastic simulation framework DairyHealthSim (DHS)© was employed to model mastitis control in dairy cows. This model was linked to both a mean-variance optimization approach and a marginal abatement cost curve (MACC) analysis. Scenarios considered included three antimicrobial (AM) dry-off protocols, five barn hygiene conditions, five milking hygiene levels, and three milk withdrawal schemes. The first set of results showed comparable economic returns between the blanket and selective dry-off strategies, though it highlighted the compromise between lowering AMU and increased farmer workload. The second outcome revealed the optimal animal-level exposure to antimicrobials (ALEA). The MACC evaluation indicated that when ALEA dropped below 1.5, the average financial loss reached approximately EUR 10,000 per ALEA unit. Findings emphasize the need for integrated farm-level decision frameworks and bioeconomic assessments to guide effective public health policies.

Keywords: Dairy cattle, Economics, Mastitis, Antimicrobial usage, Farm management

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Introduction

Mastitis, an inflammatory disorder of the bovine mammary gland, varies in intensity and typically leads to reductions in milk yield and quality. It represents one of the costliest diseases in dairy farming. A recent meta-analysis estimated that each gram-positive and gram-negative mastitis case costs farmers roughly EUR 101 and EUR 457, respectively [1]. For the dairy industry, mastitis also reduces processed milk's quality and storage stability [2]. Despite significant progress in prevention and management methods over the past decades, mastitis persists as the leading cause of antimicrobial use (AMU) in dairy herds—an issue of growing societal concern.

Between 2005 and 2012, around 60% of total AMU in dairy cattle was attributed to mastitis treatment and dry-off prophylaxis, with dry-off procedures comprising roughly two-thirds of that proportion. Amid escalating antimicrobial resistance, multiple initiatives have sought to curb AMU in food animals. In France, the Ecoantibio initiative, launched in 2012, achieved an overall 45.4% decline in AMU by 2020 across all species [3], measured through the ALEA indicator [4]. However, further reduction within the French dairy sector remains difficult. Contributing factors include the complexity of mastitis etiology, the long lifespan of dairy cows, prolonged economic stress among farmers, the wide heterogeneity of production systems, and already-low AMU levels in cattle during the 2010s compared to other livestock species [5, 6].

Progress in mastitis prevention has allowed reduced AMU through improved treatment protocols and dry-off management [7], but alternative methods must be evaluated carefully to ensure farm viability and sectoral sustainability [8]. At the farm scale, three main levers for lowering mastitis-related AMU can be identified: optimizing treatment during lactation [9], implementing selective dry cow therapy (SDCT) [10], and minimizing infection risk by enhancing environmental hygiene [11].

Preventive control measures include management of drying-off, milking hygiene, barn sanitation, feeding practices, biosecurity, and data recording. These measures demand substantial time and financial investment, often with delayed economic returns because of dairy cows' long production cycles. As such, mastitis prevention decisions are intricate, with long-term implications for herd productivity and economic resilience.

This complexity underscores the necessity for integrative mastitis management approaches, incorporating both disease control and farm-level economic behavior. Most existing bioeconomic models focus primarily on financial optimization and rarely account for resource allocation trade-offs or multi-criteria decision-making, which are central to farmers' real-world choices [12].

To date, no prior study has comprehensively quantified the monetary and non-monetary costs of reducing mastitis-related AMU. Therefore, this work aimed to evaluate trade-offs among AMU reduction, farmer workload, and economic returns using the DairyHealthSim© (DHS©) stochastic bioeconomic and optimization framework. Trade-offs were further analyzed through marginal abatement cost (MACC) curves—representing costs in EUR or additional work hours per unit decrease in AMU—by examining two of the three potential AMU reduction levers, alongside three dry-off AM strategies, five barn hygiene scenarios, and five milking hygiene conditions.

Materials and Methods

Bioeconomic modeling

The DairyHealthSim© (DHS) bioeconomic sequential optimization model was employed for this analysis. Detailed applications of DHS© have been presented in prior studies [12]. The framework combines a biological simulation module with an economic optimization component. The biological model dynamically simulates the functioning of a dairy herd over time.

Treatment events were simulated on a weekly basis per individual cow, enabling calculation of the annual animal-level exposure to antimicrobials during dry-off (ALEA_DO) as well as across all lactation stages, expressed as the proportion of treated bodyweight relative to the total treatable bodyweight (Eq. 1):

$$ALEA\_DO = \text{Treated bodyweight with AM at dry-off)/(Treatable bodyweight at dry-off)} \quad (1)$$

The economic model operates as a recursive mean–variance optimization framework, representing the farmer's dynamic input allocation decisions while maximizing expected utility under specific constraints [12]. In this study, workload and antimicrobial use (AMU) were considered as the two main restrictions. The model's outputs consisted of the farmer's utility function and expected income under varying daily activity constraints.

Strategies tested and calibration

Substandard barn or parlor hygiene increases the likelihood of environmental and contagious intramammary infections [13], while maintaining high cleanliness standards reduces mastitis incidence and enhances productivity [14]. The use of selective dry cow therapy (SDCT) has been shown to lower AMU compared to blanket dry cow therapy (BDCT) [15] and may offer slight economic advantages [16]. However, inadequate SDCT application—for example, omitting an internal teat sealant [17]—can heighten mastitis risk and negatively affect profitability [18].

To assess these effects, four sets of strategic variables—milk withdrawal (W), dry-off treatment (T), housing hygiene (H), and milking hygiene (M)—were combined to create 225 simulated scenarios **(Figure 1)**.

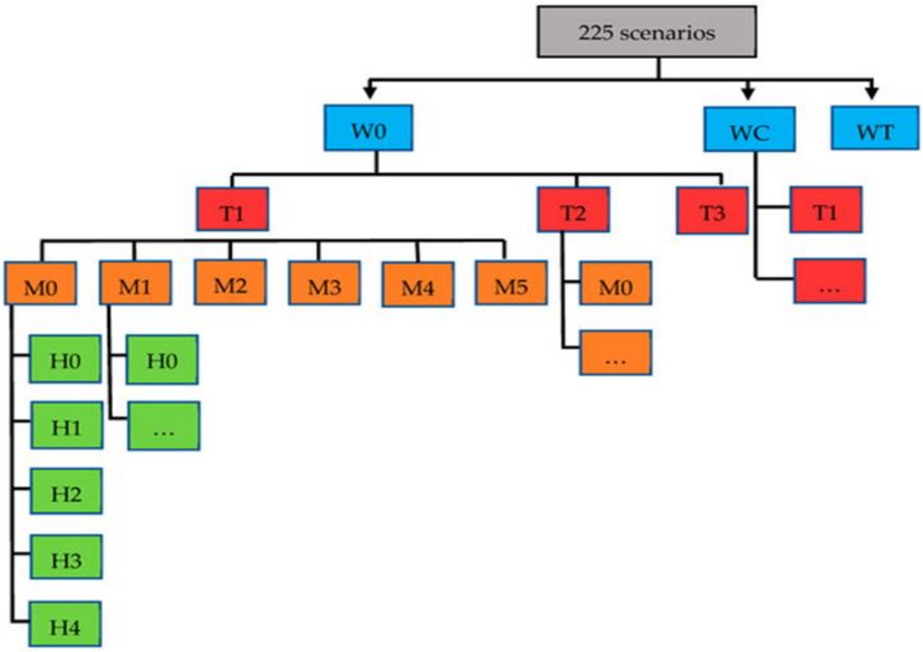


Figure 1. Schematic representation of scenario design.

- Blue boxes: Milk withdrawal strategies (W0, WC, WT)
- Red boxes: Dry-off treatment strategies (T1, T2, T3)
- Orange boxes: Milking hygiene practices (M0–M4)
- Green boxes: Housing hygiene practices (H0–H4)

The dry-off treatment strategies included:

- T1: Blanket dry cow therapy (BDCT)
- T2: SDCT implemented incorrectly
- T3: SDCT implemented properly

Both housing (H) and milking (M) hygiene sets represented five gradations of farmer management quality. Three milk withdrawal (W) approaches were modeled to account for how bulk milk somatic cell count (SCC) penalties could affect farm returns.

All strategies for T, H, and M were expected to alter mastitis incidence, thereby influencing both AMU and labor requirements **(Table 1)**. Each strategy also impacted economic performance indicators. The epidemiological and financial outputs of the model were calculated as annual averages over 10 simulated years with 50 iterations. Parameter settings for scenario calibration are summarized in **Table 1**.

Table 1. Overview and simulated impacts of milk withdrawal (W), dry-off treatment (T), housing hygiene (H), and milking hygiene (M) strategies.

Strategy	Description	Impact on Mastitis Risk and Resources
W (Milk Withdrawal)		
W0: No milk withdrawal	Milk from a cow is excluded from the bulk tank if SCC exceeds 10,000,000 cells/mL.	—
WC: Strict cow-level SCC threshold	Milk from a cow is excluded from the bulk tank if SCC exceeds 800,000 cells/mL.	—
WT: Hybrid cow-and-tank SCC threshold	Milk from a cow is excluded from the bulk tank if SCC exceeds 800,000 cells/mL **only when** bulk tank SCC exceeds 300,000 cells/mL.	—
T (Dry-Off Treatment)		

T1: Blanket dry-cow therapy (common practice)	All cows receive systematic antibiotic dry-cow therapy.	[19]
T2: Basic selective dry-cow therapy	Antibiotic dry-cow therapy only for cows with SCC > 250,000 cells/mL in the previous month.	Relative risk = 2 for clinical mastitis up to 14 weeks in milk (WIM) in untreated cows (<250,000 cells/mL) vs. blanket therapy [20].
T3: Enhanced selective dry-cow therapy	Antibiotic dry-cow therapy for cows with SCC > 250,000 cells/mL in the previous month; internal teat sealant for all others.	Relative risk = 1 for clinical mastitis in both antibiotic-treated and teat-sealant cows [21].
H (Housing Hygiene)		
H0: Excellent housing hygiene	High straw bedding and elevated labor input. Lactating: 4–6 kg straw/cow/day + 12 s/cow; Dry: 5 kg straw/cow/day.	Relative risk of clinical mastitis = 0.7.
H1: Good housing hygiene	Moderate straw increase with reduced labor. Lactating: 3–5 kg straw/cow/day + 6 s/cow; Dry: 5 kg straw/cow/day.	Relative risk of clinical mastitis = 0.8.
H2: Standard housing hygiene	Baseline straw and recommended labor. Lactating: 2–3 kg straw/cow/day + recommended time; Dry: 3 kg straw/cow/day.	Relative risk of clinical mastitis = 1.
H3: Suboptimal housing hygiene	Reduced straw and modest labor savings. Lactating: 1.5–3 kg straw/cow/day − 6 s/cow; Dry: 1.5 kg straw/cow/day.	Relative risk of clinical mastitis = 1.25.
H4: Poor housing hygiene	Minimal straw and substantial labor savings. Lactating: 1.5–3 kg straw/cow/day − 12 s/cow; Dry: 1.5 kg straw/cow/day.	Relative risk of clinical mastitis = 1.5.
M (Milking Parlor Hygiene)		
M0: Superior parlor hygiene	Intensive protocols with added labor and consumables. +1 min/cow/day + EUR 0.0452.	Relative risk of clinical mastitis = 0.7.
M1: High parlor hygiene	Enhanced protocols with moderate extras. +30 s/cow/day + EUR 0.0226.	Relative risk of clinical mastitis = 0.8.
M2: Standard parlor hygiene	Recommended time and consumables only.	Relative risk of clinical mastitis = 1.
M3: Degraded parlor hygiene	Reduced labor, no extra consumables. −7 s/cow/day + EUR 0.	Relative risk of clinical mastitis = 1.25.
M4: Severely degraded parlor hygiene	Major labor reduction, no extra consumables. −15 s/cow/day + EUR 0.	Relative risk of clinical mastitis = 1.5.

Notes:
1. Relative risk estimations are derived from expert opinion.
2. Additional or saved time is expressed relative to average management practices.
3. Consumables include sanitizers, disinfectants, drying towels, paper towels, and gloves.

Farmer's ALEA marginal abatement Cost (MAC)

At the farm scale, the marginal abatement cost (MAC) of antimicrobial exposure quantifies the economic loss associated with lowering ALEA by one unit. In this framework, MAC was defined as the variation in income caused by modifying the production strategy to achieve a one-unit decrease in ALEA. This principle mirrors economic theory used in environmental pollution control, where efficiency is achieved when a target is met at minimal cost [22].

To calculate the farmer-level MAC, simulated inputs (ALEA or labor time) and corresponding incomes were sorted in ascending order. The dependent variable for each milk withdrawal scenario (W) was then obtained using Eq. 2.

$$Income_i = f(ALEA_i, Time_i, X_i) \quad (2)$$

The marginal abatement cost of ALEA (MACALEA) was ultimately expressed as the quotient of the change in income divided by the change in ALEA for each simulated scenario (Eq. 3):

$$MAC_{ALEAi} = (\Delta Income_i/\Delta ALEA_i) = (Income_i - Income_{i-1})/(ALEA_i - ALEA_{i-1}) \quad (3)$$

In the same manner, the marginal income corresponding to each extra unit of time (denoted as MITimei) was determined according to Eq. 4:

$$MI_{Timei} = (\Delta Income_i/\Delta Time_i) = (Income_{i+1} - Income_i)/(Time_{i+1} - Time_i) \quad (4)$$

The graphical depiction of MACALEAi illustrates the marginal abatement cost curve (MACC) for ALEA. This curve enabled the determination of the optimal ALEA level, characterized by a zero marginal cost point.

Results and Discussion

Biological effects of farmers' management strategies

As anticipated, the milk withdrawal approach had a substantial impact on the amount of milk sold. Strategies WT and W0 produced nearly equivalent milk yields and income levels, while WC resulted in lower milk output and profitability, particularly under poor hygiene conditions. Within each milk withdrawal approach, deteriorating housing or milking hygiene led to progressively lower milk production (left to right within strategy T), with this effect most pronounced for T2. Under T2 and unsanitary conditions, clinical and subclinical mastitis cases rose sharply due to an increased risk of infection during dry-off.

Because the milk withdrawal method only affects milk sold rather than milk produced, other epidemiological results remained similar across withdrawal strategies (W). As expected, AMU at dry-off was highest for T1, while AMU across all stages of production peaked for T2. Additionally, both low barn (H) and milking parlor (M) hygiene were associated with greater AMU across production phases. Although both selective dry-off treatments (T2 and T3) reduced antimicrobial use in dry cows, the combination of antimicrobial and teat sealant (T3) achieved superior mastitis control per unit of AMU.

Clinical mastitis prevalence reflected the pattern of antimicrobial exposure. Culling rates due to low milk yield, subclinical or recurrent mastitis were highest for T2 and lowest for T3.

Bioeconomic optimization for identifying optimal farmer strategies

Findings revealed that WT_T3 consistently represented the most effective management option **(Table 2)**. When W0 or T3 were not optimal, differences in risk-adjusted income between strategies were minimal. The trade-off between AMU reduction and farmer workload was also evident **(Table 2)**. For producers seeking to lower AMU while maintaining reasonable labor input, housing hygiene should be prioritized over milking parlor hygiene—for instance, M2_H1 and M2_H0 reduced AMU by approximately 10% and 20%, respectively, with limited added effort.

If labor constraints were relaxed, AMU reduction was achieved more efficiently by enhancing milking hygiene—M0_H3 and M0_H2 yielded 10% and 20% AMU reductions, though requiring substantial extra labor. Considerable AMU reduction demanded a sharp increase in workload, with additional time devoted to both barn and parlor sanitation. No strategy produced a significant AMU decrease (over 10%) while keeping additional work below 35 hours (gray cells in **(Table 2)**).

Table 2. Optimal utility scenarios according to time and ALEA (animal-level exposure to antimicrobials) reduction constraints.

ALEA Reduction Target	0%	10%	20%	30%	40%
Maximum Additional Labor Time					
5 h/month	W0_T1_M2_H2	WT_T3_M2_H1			
10 h/month			WT_T3_M2_H0		
15 h/month				WT_T3_M1_H3	
20 h/month					WT_T3_M1_H1
25 h/month					
30 h/month		W0_T3_M0_H3			

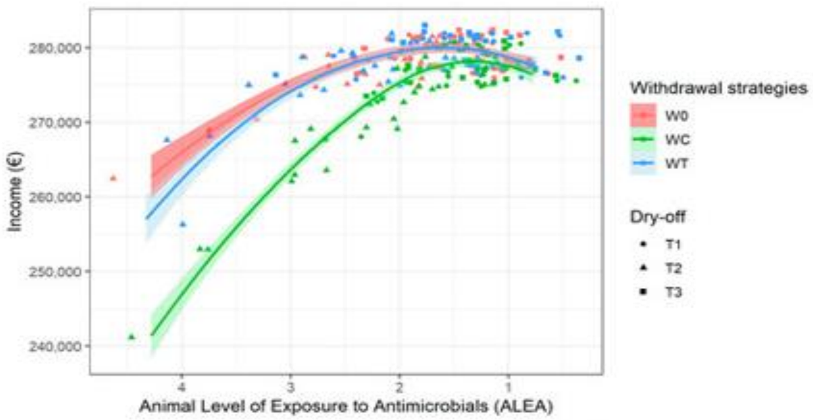
35 h/month			WT_T3_M0_H2	WT_T3_M1_H1	
40 h/month					WT_T3_M0_H0
Unlimited					

Revenue changes between scenarios were notable. Although excluding workload from income estimates is restrictive, results indicated that moderate-to-good hygiene led to the highest profitability, with only marginal gains under very high hygiene levels compared to moderate ones.

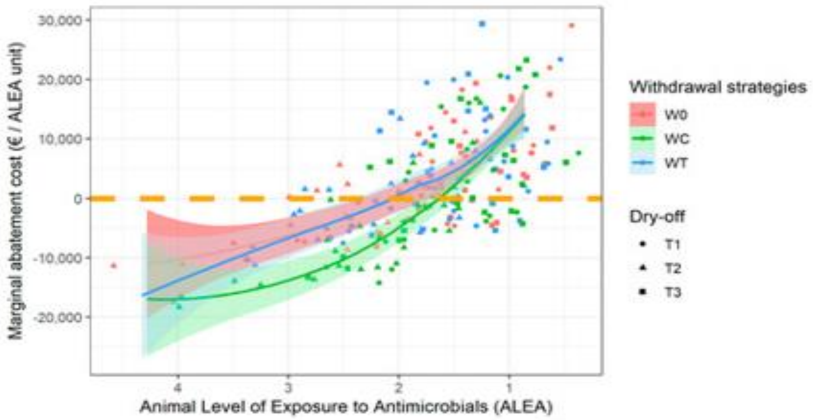
Marginal abatement curve (MAC) analysis

Aggregating all scenarios enabled estimation of the average income per ALEA level **(Figure 2a)** and its marginal variation **(Figure 2b)**. Average income per ALEA followed an inverted U-shaped pattern, with low income at high ALEA values and a gradual decline at very low ALEA levels. For W0 and WT (the main focus scenarios), income trends by ALEA were nearly identical, peaking between 1.75 and 2. The top 10% of incomes occurred for ALEA values of 1–2. The MAC reached zero at ALEA = 2, representing the optimal condition, though substantial income variation was observed within this range.

The negative correlation between ALEA and MAC **(Figure 2b)** confirmed that increased antimicrobial exposure led to decreased income. For W0 and WT, the MAC curve was almost linear, with an average slope equivalent to EUR 10,000 per unit of ALEA reduction when ALEA < 2; each unit reduction in ALEA cost farmers approximately EUR 10,000, whereas for ALEA > 2, lowering ALEA resulted in a financial gain.



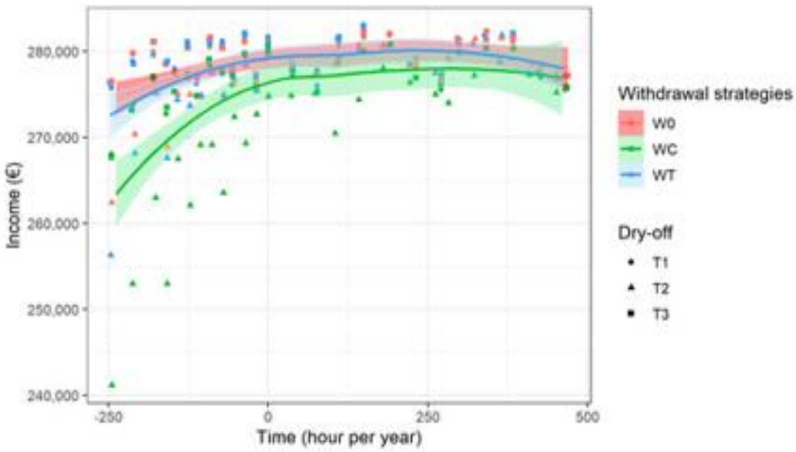
a)



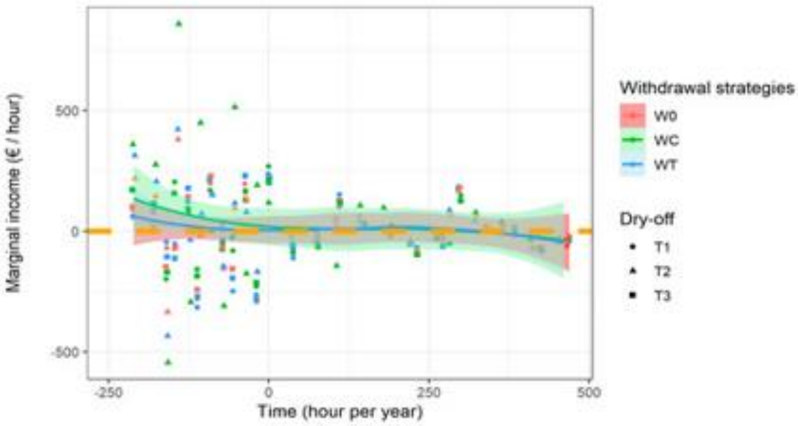
b)

Figure 2. Average income (a) and ALEA marginal abatement cost (b) according to ALEA level. Colors represent milk withdrawal strategies (W0, WC, WT), while symbols indicate dry-off treatment strategies (T1, T2, T3).

Likewise, the average income per unit of labor time **(Figure 3a)** displayed an inverted U-shape with a broad plateau. The time variable denoted extra workload for hygiene maintenance in barns and parlors, where "zero time" indicated average hygiene without added infection risk. Reducing labor below this point substantially decreased income, whereas increasing it only yielded minor or even negative returns beyond 450 additional hours annually. This "average hygiene" baseline accounted for 98% of the maximum income across all simulations. Moreover, the marginal income relative to additional labor emphasized that strategies near the average hygiene level offered the most efficient economic outcome, showing minimal incentive to further improve hygiene **(Figure 3b)**. For W0 and WT, the first extra hour of work generated roughly EUR 75/hour, but the marginal benefit rapidly dropped to near zero, and eventually became negative with excessive labor inputs.



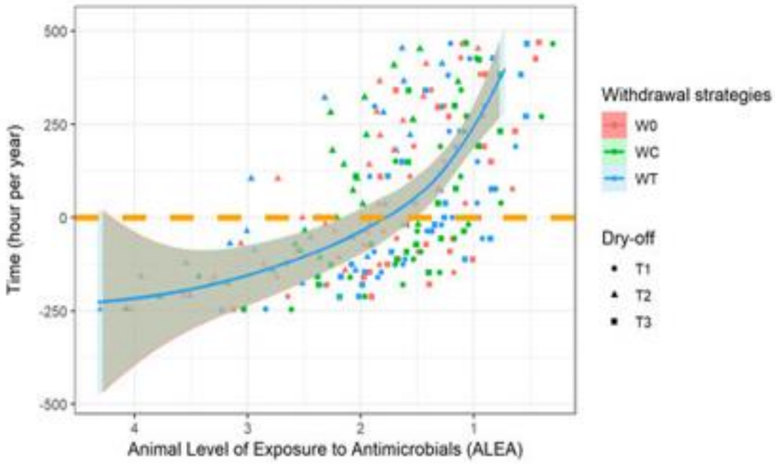
a)



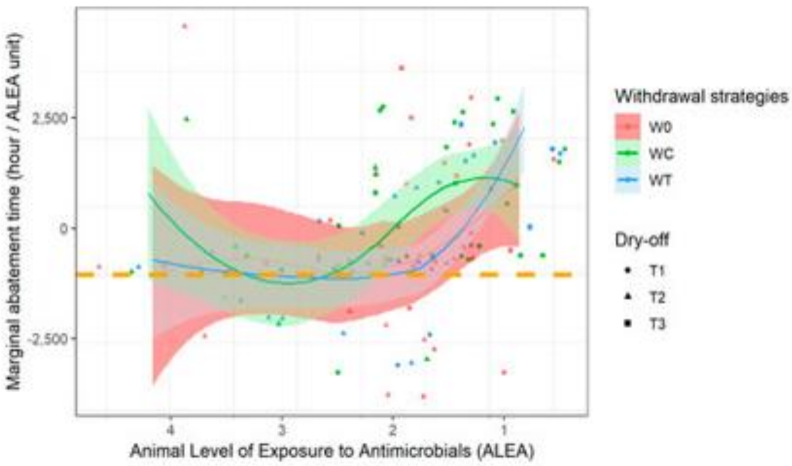
b)

Figure 3. Average income (a) and marginal income related to additional work time (b) as a function of yearly extra labor required for hygiene improvement. The colors indicate milk withdrawal approaches (W0, WT, and WC), while the symbols correspond to the dry-off treatment methods (T1, T2, and T3).

As the optimization analysis demonstrated that no strategy could considerably lower ALEA without added labor for hygiene activities, the relationship between increased work hours and ALEA was further assessed **(Figure 4a)**. A declining exponential pattern was identified between ALEA and annual extra working time, revealing that smaller increments of labor were needed to reduce ALEA among high-to-moderate AM users, whereas far greater time investment was required to achieve further ALEA reduction in low AMU groups, particularly for ALEA values under 1.75–2. The substitution coefficients between ALEA and hygiene-related time were 343, 210, and 344 h/year for T1, T2, and T3, respectively (T2 < T1, T3; $p < 0.001$). The marginal curve for time variation with ALEA **(Figure 4b)** showed a non-monotonic behavior, reflecting substitution between time spent on barn versus milking parlor cleanliness. For WT and W0, the optimal ALEA range appeared between 2 and 1.4. Beyond this range, the marginal time required for ALEA reduction rose sharply, showing a significant loss in efficiency due to excessive hygiene effort.



a)



b)

Figure 4. Annual extra labor time required for hygiene maintenance (a) and marginal abatement time for ALEA (b) relative to ALEA levels. The colors denote the milk withdrawal methods (W0, WC, and WT), and the symbols indicate dry-off treatments (T1, T2, and T3).

This research examines the marginal abatement cost (MAC) of antimicrobial use (AMU) by assessing the trade-offs between mastitis-related AMU reduction, labor input, and farm profitability. Numerous previous works have reported how management interventions influence intramammary infections and, consequently, AMU in dairy production [23, 24]. The modeled farm strategies here represent various levels of AMU related to mastitis management, primarily focusing on the adoption of selective dry cow therapy (SDCT) in different implementation contexts combined with hygiene management. The findings support the initial hypothesis that SDCT adoption decreases animal exposure to antimicrobials. A properly implemented SDCT (T3) showed both epidemiological and economic advantages over blanket dry cow therapy (BDCT, T1) [10, 16], while improper SDCT without teat sealant (T2) was linked to poorer economic outcomes [17]. Though hygiene enhancement poses challenges for farmers—mainly in terms of increased workload—its application in udder health programs can notably reduce infections, AMU, and overall economic losses [25, 26]. The simulation outcomes spanned a realistic range of hygiene management consequences, encompassing higher clinical mastitis rates [11] and significant preventive costs [27], quantified in both financial and non-financial dimensions.

Farmer decision-making and MAC

Reducing AMU requires considering the multifactorial criteria influencing dairy farmers' choices. Historically, the animal health viewpoint has been central to livestock economics [28]. For farmers, the main determinants of AMU are disease prevalence and the cost–benefit balance of antimicrobial treatments, both closely tied to management and sanitary decisions [29, 30]. The bioeconomic simulation model applied in this research explored a wide array of udder health and dry-off management combinations [12], integrating a marginal abatement cost framework to assess how lowering AMU impacts income and resource allocation. Since each mastitis management strategy carries distinct risks of infection, AMU levels also vary accordingly. The simulation results function as a sensitivity test to confirm the model's reliability regarding management effects on mastitis control and AM reduction.

The MAC framework originates from environmental economics, specifically pollution control theory, which defines optimal resource allocation that minimizes total abatement costs for a given environmental goal. When conceptualized as diffuse pollutants, both antimicrobial resistance (AMR) and greenhouse gases (GHGs) share comparable properties, making MAC a useful analytical tool for evaluating cost-efficient mitigation. Although AMU reduction has been recognized as having negative externalities [31], practical adoption generally depends on technical feasibility and economic justification unless regulatory measures enforce compliance. The abatement cost concept refers to expenses linked to adopting strategies that mitigate negative effects [32]. For instance, Moran *et al*. [33] explored farmers' profit-driven incentives for implementing such mitigation actions.

In this study, abatement costs were adapted to the dairy farming context, focusing particularly on prevention-related costs. Employing the MAC perspective enabled:

1. Evaluating disease control impacts on production losses [34];
2. Characterizing the benefits derived from ongoing AMU practices;
3. Demonstrating the cost-effectiveness of various mitigation strategies;
4. Offering a framework for setting realistic AMU reduction goals; and
5. Providing comparative insight across nations (e.g., UK, USA, New Zealand, Ireland, France) on agricultural mitigation strategies [35].

Empirical findings and policy implications

In this research, the marginal abatement evaluation framework was applied to assess the economic efficiency of antimicrobial use (AMU) reduction. The study provided a decision-support tool at the farm level and offered valuable insights for public policy related to AMU mitigation.

First, the analysis identified the threshold of antimicrobial use—the point at which any additional reduction in ALEA ceases to be economically beneficial for producers. The marginal curve of ALEA variation **(Figure 2)** can be interpreted bidirectionally for both increased and decreased exposure. In non-optimal situations, lowering ALEA yields additional profit (negative cost), while a rise in ALEA due to worsening hygiene results in financial loss. Both the MAC representation **(Figure 2)** and the marginal income-time curve **(Figure 3)** indicate an optimal ALEA interval of 1.5–2 **(Figure 4)**. This optimum depends on model calibration, which was grounded in international literature; thus, this range is likely relevant across various production systems but should be further validated. The identified optimum was also constrained by the limited technical options for ALEA reduction. While the ALEA–MAC displayed an approximately linear trend, the labor cost curve increased exponentially—meaning that with a constant MAC, the labor requirement for each additional unit of reduction became progressively higher, consistent with model assumptions.

Second, a novel contribution of this work lies in exploring alternatives to AMU as production inputs. The modeling approach allowed investigation of the substitutive relationship between hygiene-related labor and ALEA and the corresponding time investments needed to achieve ALEA reduction. Since farmer workload is a major management constraint that is often underestimated, its evaluation is crucial for assessing the allocation of labor across potential management strategies [27]. In this analysis, working time, as defined in the biological model, was treated as a variable factor in the economic assessment rather than as a fixed labor cost. This approach enabled refinement of the optimization outcomes by integrating the time limitation of farmers, highlighting the marginal income derived from hygiene improvements and the required effort for AMU mitigation.

The findings indicate that substantial ALEA reduction is attainable only with additional hygiene-related labor, underscoring hygiene as a central determinant of antibiotic reduction in dairy herds. The lowest time requirement to reduce ALEA occurred under the dry-off treatment scenario T2, which corresponded to the highest mastitis prevalence (≈220 h). Furthermore, time investments between barn and milking parlor hygiene were interchangeable. When aiming to minimize AMU with a limited workload, priority should be given to barn hygiene. Conversely, if time constraints are relaxed, greater AMU reductions are achieved through enhanced milking hygiene. Below the optimal ALEA range, additional hygiene effort is inefficient, whereas reducing time allocation has only minor effects on ALEA and income. The economic valuation of farmers' labor remains difficult to quantify under restricted management options. Future analyses should extend this framework to include trade-offs in time allocation among multiple dairy operations (e.g., reproduction, lameness prevention, and early disease detection). Overall, the results emphasize both the income loss associated with higher ALEA and the potential for AMU reduction through management adjustments. While hygiene-related material expenses (e.g., detergents, straw) contribute to cost, labor remains the dominant factor influencing ALEA improvements in this context, where available strategies are mostly limited to sanitation enhancements.

Third, the optimal ALEA interval (1.5–2) identified in this study also provides a policy-relevant benchmark for cost-effective intervention. Beyond this threshold, further antibiotic reduction or additional hygiene time is inefficient from the producer's standpoint, thereby justifying public-sector involvement. However, overly restrictive interventions could disrupt the dairy market chain [36]. In regions with already low AMU, peer influence and farmer networks appear to be effective technical levers for antibiotic reduction [37]. From a policy perspective, incentive-based approaches—including technical support [38] and awareness initiatives [39] implemented at the community scale [40]—are likely more effective than coercive regulation. The findings advocate for place-based, mesoeconomic strategies that tailor public actions to local contexts [41]. Public incentives that encourage or facilitate labor investment in hygiene tasks will be most effective for farmers with ALEA above the optimal range, whereas for those below the optimal level, labor-substitution measures (e.g., automation or robotic cleaning systems) may yield better results.

Conclusion

This study is among the few to analyze antimicrobial use using a marginal abatement cost (MAC) framework. The optimal AMU level identified corresponds to an ALEA of 1.5–2, balancing both income and labor considerations. The MAC was estimated at EUR 10,000 per ALEA unit for ALEA values below 1.5. The applied bioeconomic–marginal analysis approach allowed the integration of mastitis management practices as alternatives to AMU, treating both antibiotic use and labor as production inputs to assess the trade-offs among AMU reduction, workload, and economic return. Results established a critical threshold of AMU beyond which further ALEA reduction is not profitable, highlighting the need for public intervention. Beyond this point, policy-driven objectives can be achieved more cost-effectively at the collective level.

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