Journal of Agricultural Studies
ISSN 2166-0379
2026, Vol. 14, No. 2

Mathematical Modeling and Computer Simulation of a Simplified Silvopastoral System - La Aguada (Cordoba-Argentina)

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Received: March 11, 2026 Accepted: May 12, 2026 Published: August 14, 2026

doi:10.5296/jas.v14i2.23984 URL: https://doi.org/10.5296/jas.v14i2.23984

Abstract

Integrated systems, such as silvopastoral systems (SPS), are strategies for the sustainable intensification of livestock farming. The "La Aguada" Silvopastoral System (SPS-LA) in the Río Cuarto, Córdoba-Argentina, originally presents a topology of five areas. This study proposes a "Simplified La Aguada Silvopastoral System" (SPS-LAS), reduced to three areas: treeless pasture area, confinement area, and silvopastoral area. The objective was to develop and apply an optimization model for managing cattle movement in this simplified system. An integer linear programming (ILP) model was formulated to maximize animal weight gain and minimize management costs. The model was implemented and validated by computer simulation on the Octave platform, evaluating a herd of 100 animals over 12 months. The simulation, executed on a simple desktop, generated an optimal solution for herd allocation. The results indicated a preference for allocating resources to the "silvopastoral area" justified

by the lower associated cost, while the "confinement area" was used as a contingency unit. The ILP model proved to be a robust tool for planning and optimizing livestock production in simplified integrated systems.

Keywords: integer linear programming, livestock management, animal allocation

1. Introduction

The Livestock-Forestry integration (LFI), a subtype of agroforestry systems, is conceptualized as a production strategy that simultaneously or sequentially combines livestock and forestry components in the same area. This type of sustainable intensification aims to optimize land use and promote synergistic interactions between the elements of the system, moving away from the monoculture model (BALBINO et al., 2011). The introduction of the tree component in pastures mitigates the thermal stress of animals, providing significant improvements in animal welfare and performance. In addition to the direct benefits to livestock, the system contributes to the improvement of the physical, chemical and biological attributes of the soil, enhances nutrient cycling, increases carbon sequestration and allows for the diversification of income sources for rural producers (CORDEIRO et al., 2015).

According to PLEVICH et al. (2019), the Silvopastoral System - La Aguada (SSP-LA) is a livestock production model developed in Río Cuarto, Córdoba, Argentina. The structure of this system is composed of the integration of five distinct management areas: a silvopastoral area, two pasture areas without tree components (North and South), and two feedlot areas (North and South). The model is designed to allow the flow and rotation of animals between these different units, notably with the silvopastoral area acting as an exchange hub for the pasture areas, and these, in turn, connecting to their respective feedlot areas. The application of computational modeling and simulation to manage the movement of cattle between the areas, with monthly monitoring, is also detailed. The problem was mathematically structured as an Integer Linear Programming (ILP). The objective function aims to maximize the economic outcome, seeking to optimize the total weight gain of the animals at the expense of the costs incurred for an area to be suitable for receiving the herd. The model is conditioned by a set of constraints that regulate the allocation of animals and the suitability of each area. These constraints include the maximum number of animals that each area can support per month, the requirement for each animal to be in a single area each period, and the transition rules between the different subsystems. These movement rules are fundamentally dependent on the animal's live weight condition in relation to the weight stipulated for slaughter.

Although the robustness of the original SSP-LA model (VENTURA et al., 2019) is evident, its five-area topology imposes significant operational and analytical challenges. The simultaneous management of multiple pastures and feedlot areas, with complex transition rules, requires a level of control and monitoring that can become an obstacle to large-scale adoption, especially on properties with more limited management resources. Additionally, structural complexity translates into high-dimensional computational models, demanding greater effort in parameter collection and potentially increasing the computational cost to obtain optimal management solutions.

In this context, a gap emerges regarding the viability and optimization of silvopastoral systems that, although inspired by robust models such as "La Aguada," present a leaner configuration. It becomes pertinent to investigate whether a simplified topology, with fewer management areas, can represent a favorable balance between management complexity and productive efficiency. Structural simplification could reduce implementation costs and facilitate daily management, but it demands a reassessment of optimization models to adapt animal allocation strategies to the new systemic reality, justifying the development of a specific model for this reduced configuration.

2. Materials and Methods

The Simplified Silvopastoral System – La Aguada (SSP-LAS) is presented as a new productive model, whose topology is detailed in Figure 1. The structure of this system is based on the integration of three distinct management components: confinement area, treeless pasture area, and silvopastoral area. The flow diagram for animal transit within the system shows the operational interrelationships, indicating bidirectional transit between the confinement area and the treeless pasture area. Additionally, the model provides for a bidirectional rotation between the treeless pasture area and the silvopastoral area. As the name indicates, the system is a simplification of the original SSP-LA, resulting from the union of the northern and southern areas of the previous system.

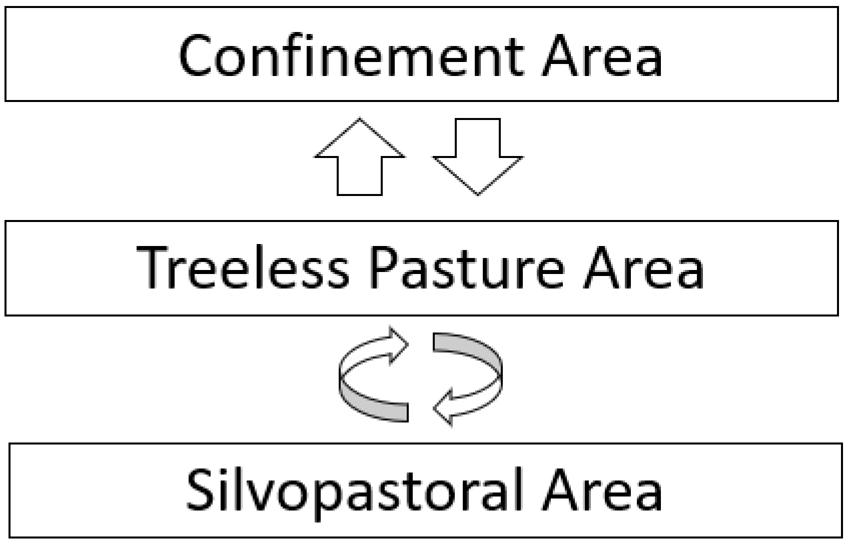

Figure 1 - Graphical Representation of the Simplified Silvopastoral System - La Aguada (SSP-LAS)

To optimize herd movement dynamics in the SSP-LAS, a PLI model was structured. The central objective of this model is to maximize animal weight gain while simultaneously minimizing operational management costs. The mathematical formulation governing the system is based on the following components: indices, parameters, decision variables, and constraints, which will be detailed subsequently.

2.1 Indices

$i = 1, \dots, n$; where n represents the number of animals in the herd considered;

$j = 1 -$ treeless pasture area, $j = 2 -$ confinement area and $j = 3 -$ silvopastoral area;

$k = 1, \dots, 12$ (months of the year);

2.2 Parameters

$PV_{ij} -$ Live weight of the animal i, in the area j (kg);

$PVA_{ij} -$ Live weight for slaughter of the animal i, in the area j (kg);

$g_{ijk} -$ Weight gained by the animal i in the area j in the month (kg);

$N_{jk} -$ Maximum number of animals allowed in the area j in the month k;

$c_{ijk} -$ Cost for the area j become fit and able to receive the animal i during the month k.

For each area j, it is $S_j = \{i: PV_{ij} < PVA_{ij}\}$ e $\overline{S_j} = \{i: PV_{ij} << PVA_{ij}\}$.

Both sets indicate animals with insufficient live weight for slaughter and extremely low live weight for slaughter, respectively.

2.3 Variables

$x_{ijk} = 1$ If the area j is ready to receive the animal i in the month k

$= 0$ Otherwise

$y_{ijk} = 1$ If the animal i is located in the area j in the month k

$= 0$ Otherwise

2.4 Restrictions

i) For each month k, the number of animals i that can remain in area j, cannot exceed the quantity of N_{jk} animals.

$$\sum_{i=1}^{n} y_{ijk} \leq N_{jk} \qquad j = 1,2,3\,; \qquad k = 1,2, \ldots .12$$

ii) Each animal i must be in one and only one area j each month k.

$$\sum_{j=1}^{3} y_{ijk} = 1 \qquad k = 1, 2, \ldots ,12; \qquad i = 1, \ldots . , n$$

iii) If animal i is in a treeless pasture area $(j = 1)$ in the month k, with a live weight strictly lower than the appropriate weight for slaughter, and in the month $k + 1$, the silvopastoral area $(j = 3)$. The area is ready to receive this animal, so the animal can be moved to the silvopastoral area in the following month $k + 1$.

$$x_{i1k} \leq y_{i3(k+1)}\ ; \quad i \in S_1 = \{i: PV_{i1} < PVA_{i1}\}\ ; \quad k = 1, \ldots . ,11$$

iv) If animal i is in the silvopastoral area $(j = 3)$ in the month k, with a live weight strictly lower than the appropriate weight for slaughter, and in the month $k + 1$, the treeless pasture area $(j = 1)$ The area is ready to receive this animal, so the animal can be moved to the northern area of treeless pasture in the following month $k + 1$.

$$x_{i3k} \leq y_{i1(k+1)}\ ; \quad i \in S_3 = \{i: PV_{i3} < PVA_{i3}\}\ ; \quad k = 1, \ldots . ,11$$

v) If animal i is in a treeless pasture area$(j = 1)$ in the month k, If the live weight is significantly lower than the appropriate weight for slaughter, the animal can be moved to the northern confinement area $(j = 2)$ in the month $k + 1$.

$$y_{i1k} \leq y_{i2(k+1)}\ ; \qquad i \in \overline{S_1} = \{i: PV_{i1} << PVA_{i1}\}\ ; \quad k = 1, \ldots . ,11$$

vi) If animal i is in the confinement area $(j = 2)$ in the month k, if the animal's live weight is strictly less than the appropriate weight for slaughter, then the animal must remain in that area for the month. $k+1$.

$$y_{i2k} \leq y_{i2(k+1)} \quad ; \quad i \in S_2 = \{i: PV_{i2} < PVA_{i2}\} \;\; ; \quad k = 1, \ldots ., 11$$

vii) If animal i is in the confinement area $(j = 2)$ in the month k, if an animal has a live weight that is significantly lower than the appropriate weight for slaughter, then that animal must remain in the same area for the following two months.

$$y_{i2k} < y_{i2(k+1)} + y_{i2(k+2)} \qquad i \in \bar{S}_2 = \{i: PV_{i2} << PVA_{i2}\}; \quad k = 1, \ldots ., 11$$

viii) Each animal must have at least one designated area in the SSP-LAS each month of the year.

$$\sum_{j=1}^{3} x_{ijk} \geq 1 \qquad i = 1, \ldots ., n; \quad k = 1, \ldots, 12$$

ix) If the animal i is in the confinement area $(j = 2)$ in the month k, If the animal's live weight is strictly less than the appropriate weight for slaughter, then the animal should not be in the silvopastoral area ($j = 3$) in the month $k+1$.

$$y_{i2k} + y_{i3(k+1)} \leq 1 \;, \quad k = 1, \ldots ., 11$$

x) If the animal i It is located in a silvopastoral area ($j = 3$) in the month k, if the live weight is strictly less than the appropriate weight for slaughter, then the animal should not be in the confinement area. $(j = 2)$ in the month $k+1$.

$$y_{i3k} + y_{i2(k+1)} \leq 1 \;, \; k = 1, \ldots ., 11$$

xi) Animal i can only occupy area j in month k if that area is available for occupation.

$$y_{ijk} \leq x_{i1k} \;, \qquad j = 1,2,3 \qquad k = 1,2, \ldots .12 \qquad i = 1, \ldots ., n$$

The PLI (Programmable Logic Interface) for optimal control of cattle movement in SSP-LAS can be represented as follows, considering that a computational language was used for numerical simulation and development of optimal solutions:

$$Maximize \sum_{i=1}^{n}\sum_{j=1}^{3}\sum_{k=1}^{12} g_{ijk}\, y_{ijk} - \sum_{i=1}^{n}\sum_{j=1}^{3}\sum_{k=1}^{12} c_{ijk}\, x_{ijk}$$

Journal of Agricultural Studies
ISSN 2166-0379
2026, Vol. 14, No. 2

Subject to:

$$\sum_{i=1}^{n} y_{ijk} \leq N_{jk} \qquad j = 1,2,3 \quad ; \quad k = 1,2, \dots .12$$

$$\sum_{j=1}^{3} y_{ijk} = 1 \qquad k = 1, 2, \dots ,12 \quad ; \quad i = 1, \dots . , n$$

$$x_{i1k} \leq y_{i3(k+1)} \;\; ; \;\; i \in S_1 = \{i: PV_{i1} < PVA_{i1}\} \;\; ; \;\; k = 1, \dots . ,11$$

$$x_{i3k} \leq y_{i1(k+1)} \;\; ; \;\; i \in S_3 = \{i: PV_{i3} < PVA_{i3}\} \;\; ; \;\; k = 1, \dots . ,11$$

$$y_{i1k} \leq y_{i2(k+1)} \;\; ; \;\; i \in \overline{S_1} = \{i: PV_{i1} << PVA_{i1}\} \;\; ; \;\; k = 1, \dots . ,11$$

$$y_{i2k} \leq y_{i2(k+1)} \;\; ; \;\; i \in S_2 = \{i: PV_{i2} < PVA_{i2}\} \;\; ; \;\; k = 1, \dots . ,11$$

$$y_{i2k} < y_{i2(k+1)} + y_{i2(k+2)} \qquad i \in \overline{S_2} = \{i: PV_{i2} << PVA_{i2}\}; \;\; k = 1, \dots . ,11$$

$$\sum_{j=1}^{3} x_{ijk} \geq 1 \qquad i = 1, \dots . , n; \quad k = 1, \dots , 12$$

$$y_{i2k} + y_{i3(k+1)} \leq 1 \; , \;\; k = 1, \dots . ,11$$

$$y_{i3k} + y_{i2(k+1)} \leq 1 \; , \;\; k = 1, \dots . ,11$$

$$y_{ijk} \leq x_{i1k} \; , \qquad j = 1,2,3 \qquad k = 1,2, \dots .12 \qquad i = 1, \dots . , n$$

$$x_{ijk}, y_{ijk} = 0,1$$

For the operationalization and validation of the proposed PLI model for the SSP-LAS, a computer simulation was employed using the *Octave* programming language, a high-level platform designed for numerical calculations. This tool was used specifically for the execution of the numerical simulation of animal flow, and for the development of optimal management solutions, as described in the PLI formulation.

3. Results and Discussion

The implemented model was validated through a numerical simulation, using the Octave programming language for processing and developing optimal solutions. The simulation was run for a planning horizon of 12 monthly periods and applied to a herd of up to 100 animal units (A1 to A100). This processing was conducted on a simple desktop, requiring a total execution time of 44,627.4 seconds. The generated results detail the optimal allocation of each animal in one of the three management areas (treeless pasture area, confinement area, or silvopastoral area) for each evaluated period, as it is presented in Table 1.

Based on the quantitative analysis of the simulation results presented (Table 1), compared with the availability of use for each animal in each period, a preference is observed in the allocation of animals to the silvopastoral area throughout the 12-month planning horizon, always sending or remaining in this area whenever this area is available for the animal, and the animal is at an adequate weight to occupy it. Although the values demonstrate a relatively balanced rotation system, they also indicate that the animal is only sent to or remains in the confinement area when the animal is below or extremely below the weight it should have for its age, or there is no possibility of it leaving this area because there is no space in the treeless pasture area.

Table 1. The quantitative analysis of the simulation results

	Pasture area without trees	Confinement area	Silvopastoral area
Period 1	A4 A7 A8 A11 A12 A15 A17 A22 A25 A27 A30 A34 A35 A41 A43 A48 A53 A54 A56 A68 A69 A70 A72 A88 A89 A94 A96 A99	A1 A3 A5 A9 A10 A14 A18 A20 A21 A26 A28 A29 A31 A32 A39 A42 A44 A45 A46 A51 A52 A55 A60 A61 A62 A63 A64 A65 A66 A67 A71 A73 A74 A81 A82 A87 A90 A91 A92 A93 A95 A97 A98 A100	A2 A6 A13 A16 A19 A23 A24 A33 A36 A37 A38 A40 A47 A49 A50 A57 A58 A59 A75 A76 A77 A78 A79 A80 A83 A84 A85 A86
Period 2	A2 A3 A10 A11 A13 A14 A17 A22 A23 A24 A33 A35 A36 A37 A43 A47 A50 A61 A63 A64 A65 A66 A77 A80 A83 A85 A86 A96 A98 A99	A1 A4 A5 A9 A18 A20 A21 A26 A28 A29 A30 A31 A32 A39 A42 A44 A45 A46 A51 A52 A55 A60 A62 A67 A71 A73 A74 A81 A82 A87 A90 A91 A92 A93 A95 A97 A100	A6 A7 A8 A12 A15 A16 A19 A25 A27 A34 A38 A40 A41 A48 A49 A53 A54 A56 A57 A58 A59 A68 A69 A70 A72 A75 A76 A78 A79 A84 A88 A89 A94
Period 3	A4 A7 A8 A11 A12 A15 A17 A22 A25 A26 A27 A30 A32 A34 A36 A37 A47 A48 A54 A56 A64 A65 A66 A67 A68 A70 A71 A72 A75 A76 A78 A85 A88 A89 A92 A98	A1 A3 A5 A9 A10 A18 A20 A21 A28 A29 A31 A39 A42 A44 A45 A46 A51 A52 A55 A60 A62 A73 A74 A81 A82 A87 A90 A91 A93 A95 A97 A100	A2 A6 A13 A14 A16 A19 A23 A24 A33 A35 A38 A40 A41 A43 A49 A50 A53 A57 A58 A59 A61 A63 A69 A77 A79 A80 A83 A84 A86 A94 A96 A99
Period 4	A1 A2 A5 A8 A11 A14 A17 A23 A24 A26 A30 A35 A36 A37 A40 A41 A43 A50 A54 A56 A57 A63 A76 A77 A78 A80 A83 A94 A96 A98 A99	A3 A9 A10 A18 A20 A21 A28 A29 A31 A32 A39 A42 A44 A45 A46 A51 A52 A55 A60 A62 A64 A66 A67 A70 A71 A73 A74 A81 A82 A85 A87 A90 A91 A92 A93 A95 A97 A100	A4 A6 A7 A12 A13 A15 A16 A19 A22 A25 A27 A33 A34 A38 A47 A48 A49 A53 A58 A59 A61 A65 A68 A69 A72 A75 A79 A84 A86 A88 A89
Period 5	A2 A4 A7 A11 A12 A13 A15 A21 A22 A27 A30 A33 A34 A35 A37 A40 A42 A47 A51 A53 A54 A56 A61 A64 A65 A67 A68 A69 A71 A72 A76 A80 A82 A85 A88 A89 A94	A3 A9 A10 A14 A18 A20 A28 A29 A31 A32 A39 A44 A45 A46 A52 A55 A60 A62 A66 A70 A73 A74 A81 A87 A90 A91 A92 A93 A95 A97 A98 A100	A1 A5 A6 A8 A16 A17 A19 A23 A24 A25 A26 A36 A38 A41 A43 A48 A49 A50 A57 A58 A59 A63 A75 A77 A78 A79 A83 A84 A86 A96 A99
Period 6	A1 A5 A8 A11 A13 A16 A17 A21 A22 A24 A25 A33 A40 A43 A54 A57 A63 A64 A70 A75 A76 A77 A78 A83 A86 A92 A96 A99	A3 A9 A10 A14 A18 A20 A28 A29 A31 A32 A39 A44 A45 A46 A51 A52 A55 A60 A62 A66 A67 A73 A74 A81 A87 A90 A91 A93 A95 A97 A98 A100	A2 A4 A6 A7 A12 A15 A19 A23 A26 A27 A30 A34 A35 A36 A37 A38 A41 A42 A47 A48 A49 A50 A53 A56 A58 A59 A61 A65 A68 A69 A71 A72 A79 A80 A82 A84 A85 A88 A89 A94
Period 7	A2 A3 A7 A15 A21 A22 A23 A27 A34 A35 A37 A43 A46 A47 A48 A51 A53 A55 A56 A64 A66 A68 A71 A80 A82 A85 A88 A89 A92 A94 A98	A9 A10 A14 A18 A20 A28 A29 A31 A32 A39 A44 A45 A52 A60 A62 A67 A70 A73 A74 A81 A87 A90 A91 A93 A95 A97 A100	A1 A4 A5 A6 A8 A11 A12 A13 A16 A17 A19 A24 A25 A26 A30 A33 A36 A38 A40 A41 A42 A49 A50 A54 A57 A58 A59 A61 A63 A65 A69 A72 A75 A76 A77 A78 A79 A83 A84 A86 A96 A99
Period 8	A1 A2 A4 A5 A8 A10 A11 A13 A14 A17 A18 A24 A26 A35 A40 A41 A42 A43 A50 A51 A54 A56 A57 A61 A63 A66 A69 A72 A75 A77 A78 A83 A84 A89 A94 A96 A99	A9 A14 A20 A21 A28 A29 A31 A32 A39 A44 A45 A52 A60 A62 A67 A70 A71 A73 A74 A80 A81 A85 A87 A90 A91 A92 A93 A95 A97 A98 A100	A3 A6 A7 A12 A15 A16 A19 A22 A23 A25 A27 A30 A33 A34 A36 A37 A38 A46 A47 A48 A49 A53 A55 A58 A59 A64 A65 A68 A76 A79 A82 A86 A88
Period 9	A2 A3 A7 A8 A11 A12 A13 A14 A15 A21 A22 A25 A27 A32 A34 A35 A37 A40 A43 A46 A47 A51 A55 A57 A64 A65 A67 A68 A72 A81 A82 A88 A89 A99	A9 A20 A26 A28 A29 A31 A39 A44 A45 A50 A52 A56 A60 A62 A70 A71 A73 A74 A80 A85 A87 A90 A91 A92 A93 A95 A97 A98 A100	A1 A4 A5 A6 A10 A16 A17 A18 A19 A23 A24 A30 A33 A36 A38 A41 A42 A48 A49 A53 A54 A58 A59 A61 A63 A66 A69 A75 A76 A77 A78 A79 A83 A84 A86 A94 A96
Period 10	A1 A2 A4 A5 A8 A10 A11 A16 A17 A18 A23 A24 A25 A26 A30 A35 A37 A42 A43 A47 A48 A51 A53 A54 A63 A71 A75 A76 A77 A78 A80 A83 A85 A94 A96 A98	A9 A14 A20 A21 A22 A28 A29 A31 A32 A39 A44 A45 A50 A52 A56 A60 A62 A70 A73 A74 A87 A90 A91 A92 A93 A95 A97 A100	A6 A7 A12 A13 A15 A19 A27 A33 A34 A36 A38 A40 A46 A49 A55 A57 A58 A59 A61 A64 A65 A66 A67 A68 A69 A72 A79 A81 A82 A84 A86 A88 A89 A99

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ISSN 2166-0379
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Period 11	A7 A10 A11 A16 A14 A15 A21 A22 A27 A32 A35 A36 A37 A40 A41 A46 A51 A54 A55 A57 A66 A67 A68 A69 A71 A76 A80 A81 A82 A84 A85 A88 A89 A92 A96 A99	A3 A9 A20 A28 A29 A31 A39 A43 A44 A45 A50 A52 A56 A60 A62 A70 A73 A74 A87 A90 A91 A93 A94 A95 A97 A98 A100	A1 A2 A4 A5 A6 A8 A12 A13 A17 A18 A19 A23 A24 A25 A26 A30 A33 A34 A38 A42 A47 A48 A49 A53 A58 A59 A61 A63 A64 A65 A72 A75 A77 A78 A79 A83 A86
Period 12	A1 A2 A4 A5 A12 A17 A18 A23 A26 A30 A32 A34 A35 A40 A47 A49 A50 A53 A60 A61 A63 A75 A76 A77 A79 A83 A85 A86 A92 A93 A95	A3 A9 A10 A11 A14 A16 A20 A28 A29 A31 A37 A39 A43 A44 A45 A52 A56 A57 A62 A66 A70 A73 A74 A87 A90 A91 A94 A97 A98 A100	A6 A7 A8 A13 A15 A19 A21 A22 A24 A25 A27 A33 A38 A41 A42 A46 A48 A51 A54 A55 A58 A59 A64 A65 A67 A68 A69 A71 A72 A78 A80 A81 A82 A84 A88 A89 A96 A99

The choice of the silvopastoral area in the simulation is due to it having the lowest cost for fattening cattle, while avoiding sending or keeping animals in the confinement area, since this has the worst cost for fattening cattle, thus proving the efficiency of the mathematical model presented.

4. Conclusion

This study demonstrated the development and application of an optimization model for managing livestock movement in the silvopastoral system - La Aguada Simplified (SSP-LAS). Formulating the problem as integer linear programming (ILP), aiming to maximize animal weight gain and minimize management costs, proved to be a viable approach for structuring allocation decisions. Computer simulation validated the model's operability for the proposed scenario and, even when executed on simple computing equipment, resulted in a detailed optimal solution for the management flow.

The analysis of the results indicated that the model prioritizes the silvopastoral area as the central component of fattening, being preferentially used when the animal's conditions and the availability of the area are met. In contrast, the confinement area was designated as a contingent management unit, used primarily for animals that did not reach the appropriate weight, or when the other areas reached their limit capacity. The proposed PLI model, therefore, constitutes a robust tool for planning and optimizing livestock production in simplified integrated systems.

Acknowledgments

Not applicable.

Author contributions

Not applicable.

Funding

Not applicable.

Competing interests

Not applicable.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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