
# Artificial Intelligence Framework for Bioenergetic Flow Audit and Thermal Entropy: A Precision Approach in the Brazilian Semiarid

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**A paper from the Proceedings of the**
**17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture**
**13-15 July 2026**
**Porto Alegre, Brazil**

***Abstract.***

*Extensive livestock farming in the Brazilian semiarid faces productivity bottlenecks masked by weed competition, where invasive plants mimic vegetative vigor but impose thermal and nutritional stress on the herd. This study aimed to develop and validate the "Predict-IA" framework, a bioenergetic audit tool based on Artificial Intelligence to quantify systemic entropy and "energy leakage" in degraded pastures. A ten-year time series (2015-2025) of Sentinel-2 multispectral data processed in Google Earth Engine was used, integrated with local climatic and zootechnical data from Carinhanha, Bahia. Through the Random Forest algorithm, the "Ghost Synchrony" phenomenon was identified in 73.9% of the analyzed period, where high EVI levels did not result in weight gain due to low grazing efficiency (< 60%) and high thermoregulatory costs (Metabolic Slavery). Results indicate a drop in real ADG from 0.650 kg/day to 0.170 kg/day, generating an accumulated loss of 27.36 @/ha ($4,200/ha equivalent). Simulations demonstrated that transitioning to Crop-Livestock Integration (CLI) with Cotton increases bioenergetic retention from 26.1% to 82%, mitigating thermal entropy. It is concluded that precision management, focused on "energetic cleaning," is imperative for economic viability and carbon sequestration in tropical livestock.*

***Keywords.***

*Remote Sensing, Random Forest, Metabolic Slavery, Sentinel-2, CLI.*

## 1. Introduction

Extensive livestock farming in the Brazilian semiarid faces critical productivity challenges, often exacerbated by misguided diagnoses based solely on the visual appearance of pastures. In regions such as Carinhanha, Bahia, weed competition dynamics establish what is termed a "Green Bridge," where invasive plants mimic satisfactory vegetative vigor indices but offer no nutritional support or thermal comfort. This botanical disorder alters the system's energy balance, necessitating the use of Precision Agriculture tools to differentiate productive biomass from degrading biomass.

Conventional monitoring methodologies based on static vegetation indices like NDVI fail to capture microclimatic disturbances induced by canopy heterogeneity. The presence of invasive plants not only competes for nutrients and water but acts as a thermal energy sink, raising the surface radiometric temperature (Trad) and imposing a state of continuous abiotic stress on cattle. From this perspective, precision agriculture must evolve toward a bioenergetic analysis capable of quantifying how much of the energy available in the ecosystem is effectively retained by the animal as tissue (meat) and how much is dissipated as entropy.

In this context, Artificial Intelligence emerges as a catalyst for interpreting large volumes of geospatial and climatic data (Oliveira Filho et al., 2024). Through the integration of high-resolution orbital sensors, such as the Sentinel-2 constellation, and machine learning algorithms, it becomes possible to audit the thermodynamic flow of the ranch in real-time. The framework proposed in this study, termed Predict-IA, utilizes the "Energy Leakage" concept to identify moments when the system enters an operational deficit, allowing the producer to anticipate phytosanitary interventions before economic damage becomes irreversible.

The objective of this paper is to present the results of a ten-year bioenergetic audit (2015-2025) using Random Forest to map the efficiency of the pastoral system in Carinhanha/BA. It aims to demonstrate the correlation between systemic disorder (Entropy) and the drop in Average Daily Gain (ADG), validating the use of AI as a decision support tool. Ultimately, the work proposes a paradigm shift: pasture management must be viewed as "Bioenergetic Engineering."

## 2. Theoretical Framework

The conceptual basis of this work is founded on the Second Law of Thermodynamics applied to biological systems (Sousa et al., 2020), where the efficiency of a pastoral ecosystem is measured by its capacity to minimize entropy. In degraded pasture environments, solar radiant energy is dissipated as sensible heat due to low soil cover. This phenomenon creates a high-entropy microclimate, forcing the animal to divert metabolic resources from production to thermoregulation, characterizing "energy leakage."

In this scenario, the concept of "Metabolic Slavery" becomes central. When the surface radiometric temperature (Trad) exceeds the cattle's thermal comfort limit, metabolizable energy intended for meat production is consumed by respiratory work and endogenous heat dissipation (Ferreira et al., 2006). The animal enters a positive feedback loop of energy expenditure, where the effort to feed in a degraded environment consumes the very energy the food would provide.

To monitor this dynamic, the Enhanced Vegetation Index (EVI) is superior to NDVI by mitigating soil signal and atmospheric aerosols, allowing for a more accurate estimation of active green biomass even under high radiation. Machine Learning models, such as Random Forest, identify non-linear patterns and isolate "Ghost Synchrony," transforming spectral data into indicators of profit and sustainability (Gorelick et al., 2017).

## 3. Methodology

A Data Fusion process was utilized, covering ten years of data (2015-2025) from Carinhanha, BA. Sentinel-2 (MSI) orbital data were processed via the Google Earth Engine (GEE) API. EVI and NDWI indices were calculated at a 10-meter resolution to capture structural heterogeneity (Gorelick et al., 2017).

A database of climatological (Trad, precipitation) and zootechnical variables was structured. The framework calculated the "Chaos Index" based on the divergence between energy captured and energy converted into meat, isolating leakage caused by weed competition (Bossoi et al., 2024).

The Predict-IA analytical engine utilized a Random Forest Regressor (Breiman, 2001) with 100 estimators. Predictive variables: EVI, average temperature, and systemic entropy. Target variables: ADG and Carbon Balance. Systemic rehabilitation simulations were performed via No-Till systems and Crop-Livestock Integration (CLI) with Cotton, focusing on entropy reduction during the "Golden Window" of biological response.

## 4. Results and Discussion

The initial results revealed a pronounced hysteresis cycle in the biological response of pastures in Carinhanha, BA. By correlating cumulative precipitation with the Enhanced Vegetation Index (EVI), the framework detected that the ecosystem does not respond linearly to water input. There is a "memory lag" of approximately 15 to 20 days caused by accumulated thermal stress. During the dry-to-wet transition, the recovery rate is significantly lower than the degradation rate observed in the wet-to-dry transition. This indicates that available metabolic energy is primarily consumed in repairing degraded tissues and combatting weed competition rather than producing palatable leaf biomass. This hysteresis phenomenon serves as the primary indicator of systemic vitality loss, which the Predict-IA framework identifies as "Thermodynamic Fatigue."

One of the most disruptive findings was the identification of "Ghost Synchrony." The AI algorithm detected that in 73.9% of the analyzed decade, high EVI levels recorded by Sentinel-2 did not correspond to animal weight gains. This divergence occurs because aggressive C4 invasive plants mimic a healthy canopy (high chlorophyll reflectance) but offer extremely low nutritional value and fiber digestibility. The orbital sensor registers the "green," but the AI, by cross-referencing this with surface radiometric temperature (Trad), classifies this biomass as "productive noise." This "Green Illusion" masks soil degradation, leading producers to erroneous management decisions based on a false perception of carrying capacity.

The application of the framework revealed a drastic erosion in zootechnical performance. While the genetic potential for tropical grasses under optimized conditions is 0.650 kg/day, the real ADG (Average Daily Gain) fluctuated around 0.170 kg/day. This 73.8% drop in efficiency is not due to genetic deficiency but to "Metabolic Slavery." Predict-IA demonstrated that metabolizable energy is diverted to satisfy the high cost of thermoregulation and locomotion. Furthermore, the "Forage Harvest Efficiency" dropped below the 60% threshold during high-entropy months. The cattle spend more energy searching for and selecting bites among invasive weeds than the energy they effectively absorb, creating a negative caloric balance.

The framework generated the Systemic Health Index (S.I.S), acting as an "electrocardiogram" of the pasture. Results showed that the system reached "Immunological Failure" points multiple times. In these periods, the forage plant's regrowth capacity is nil because its root carbohydrate reserves are exhausted to maintain basal survival under extreme thermal stress. The AI detected that the cost of pasture recovery increases fourfold when reaching this "red zone," as weeds have already colonized the ecological niche, preventing biological resynchronization through simple methods.

Translating bioenergetic flows into financial metrics revealed an alarming scenario of "Evaporated Profit." The thermodynamic inefficiency resulted in an accumulated loss of 27.36 @/ha over ten years. Financially, this represents a leakage of R$ 23,695.50 per hectare in unrealized revenue. Additionally, the AI identified a 40% higher risk of spittlebug (deois flavopicta) infestations in high-entropy areas. The invasive plants act as a "Green Bridge" and thermal shelter for pests, maintaining the residual moisture necessary for nymph hatching even in adverse periods, further reducing the longevity of the forage active.

Simulations indicated that introducing high leaf area index cover crops, such as Cotton, acts as a "thermodynamic stabilizer." The Cotton architecture in CLI systems promotes biological suppression via shading, reducing direct solar radiation on the soil and lowering surface temperature by up to 8°C. This transition raised energy retention efficiency from 26.1% to 82%. The "Revenue Leap" projected by the AI shows that per-hectare billing can be up to 10 times higher than the "dirty" extensive model, proving that CLI is not merely an agricultural choice, but a thermodynamic necessity to halt the biological insolvency of the ranch.

## 5. Conclusion

Pasture degradation in the semiarid is a thermodynamic collapse. The Predict-IA framework proved that weed management is not a cost, but bioenergy recovery. Transitioning to CLI and No-Till systems reverses systemic entropy and restores profitability, offering a scientific basis for real-time carbon audits and precision livestock farming.

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