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A fuzzy multi-objective linear programming approach for integrated sheep farming and wildlife in land management decisions: a case study in the Patagonian rangelands

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Wildlife is part of the Patagonian rangelands sheep farming environment, with the potential of providing extra revenue to livestock owners. As sheep farming became less profitable, farmers and ranchers could focus on sustainable wildlife harvesting. It has been argued that sustainable wildlife harvesting is ecologically one of the most rational forms of land use because of its potential to provide multiple products of high value, while reducing pressure on ecosystems. The guanaco (*Lama guanicoe*) is the most conspicuous wild ungulate of Patagonia. Guanaco ?bre, meat, pelts and hides are economically valuable and have the potential to be used within the present Patagonian context of production systems. Guanaco populations in South America, including Patagonia, have experienced a sustained decline. Causes for this decline are related to habitat alteration, competition for forage with sheep, and lack of reasonable management plans to develop livelihoods for ranchers. In this study we propose an approach to explicitly determinate optimal stocking rates based on trade-offs between guanaco density and livestock grazing intensity on rangelands.

The focus of our research is on finding optimal sheep stocking rates at paddock level, to ensure the highest production outputs while: a) meeting requirements of sustainable conservation of guanacos over their minimum viable population; b) maximizing soil carbon sequestration, and c) minimizing soil erosion. In this way, determination of optimal stocking rate in rangelands becomes a multi-objective optimization problem that can be addressed using a Fuzzy Multi-Objective Linear Programming (MOLP) approach. Basically, this approach converts multi-objective problems into single-objective optimizations, by introducing a set of objective weights. Objectives are represented using fuzzy set theory and fuzzy memberships, enabling each objective function to adopt a value between 0 and 1. Each objective function indicates the satisfaction of the decision maker towards the respective objective. Fuzzy logic is closer to intuitive thinking used by decision makers, making it a user-friendly approach for them to select alternatives. The proposed approach was applied in a study area of approximately 40,000 hectares in semiarid Patagonian rangelands where extensive, continuous sheep grazing for wool production is the main land use.

Multi- and hyper-spectral data were combined with ancillary data within a GIS environment, and used to derive maps of forage production, guanacos density, soil organic carbon and soil erosion. Different scenarios, with different objectives weights were evaluated. Results showed that under scenario 1, where livestock production is predicted to have the highest values, guanaco numbers decrease substantially as well as soil carbon sequestration, and soil erosion exhibit the highest values. On the other hand, when guanaco population is prioritized, livestock production has the lowest value. A compromise alternative resulted from a scenario where variables are assigned same weight; under this condition, high livestock production is predicted, while conservation of guanaco population is sustainable, carbon sequestration is maximized and soil erosion minimized.