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A simulation-based approach for evaluating the effects of farm type, management, and rainfall on the water footprint of sheep grazing systems in a semi-arid environment

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ABSTRACT

Central Chile has a semi-arid, Mediterranean-type climate, characterized by mild temperatures and irregular and unreliable winter rainfall. Meat sheep production managed in extensive systems is an important agricultural activity of the area. A dynamic, stochastic, simulation sheep model was developed with the objective of assessing the water footprint of extensive lamb production in relation to factorial combinations of annual rainfall, stocking rate, and rate of supplementation of ewes and lambs. The simulation model includes two sub models that estimate grass and lamb growth respectively. The model allows estimation of the water footprint of sheep production, its partitioning into green-blue-grey water, and of tradeoffs in physical outputs. Dry (424 mm) and very dry (380 mm) years occurred in 40% of cases reported for the 1972–2014 period. Green, blue and grey water footprints were significantly affected by the variables studied. The lowest water footprint was found in average years (702 mm; 5369 L·kg of LW^{-1} sold) and increased to 7741 L·kg of LW^{-1} sold in dry years when ewes were supplemented with grain. Numerous significant interactions between yearly rainfall and feeding strategies were found that are indicative of the management challenges faced by the system. The simulation model proved to be a powerful tool to examine a variety of climatic and production scenarios in order to infer possible future trends in response to climate change and production strategies.

1. Introduction

The ever increasing demand for food production is constrained by numerous environmental conditions, water being one of the major ones, particularly in arid and semi-arid regions. Extensive rangeland-based ruminant production systems, although of limited efficiency, use rangelands that have few, if any, alternative uses. That is the case in semi-arid Central Chile, where extensive sheep systems based on year-round grazing of annual pastures and limited cereals stubbles constitute a major land use (Toro-Mujica et al., 2015), particularly among small and medium grazers located in less favored areas, as is common elsewhere (Pérez et al., 2007; Pardos et al., 2008; Morris, 2009; Ripoll-Bosch et al., 2012; Toro-Mujica et al., 2015). Extant systems are under pressure to intensify and increase efficiency, but little consideration has been given to possible environmental impacts. Toro-Mujica et al. (2015) examined the trends in sheep systems between 1997 and 2007 in Central Chile, and completed a typology of existing regional sheep systems, which permits the identification of domains of extrapolation, and constitutes the base for planning possible development and intensification paths.

As discussed by Dourte et al. (2014), a water footprint relates the system performance, its management and inputs, to the consumption of freshwater that may in the short term, become unavailable for other uses. Worldwide agriculture accounts for 92% of the blue water, 4.4% of industrial water, and 3.6% domestic water (Hoekstra and Mekonnen, 2012). Within the agricultural sector, animal production represents about a third of total water consumption (Gerbens-Leenes et al., 2013), with animal products having a much larger water footprint than crops on a weight or calorie basis (Hoekstra, 2010). Hoekstra et al. (2011) identified the water footprint as "an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time". The water footprint can be considered as composed of three parts, namely, green, blue and grey water (Hoekstra, 2010). Green water is rainfall stored in soils. Blue water is that accumulated in water streams, and grey water is the amount of required to dilute contaminants resulting from the production process to the extent that water sources maintain the desired water quality (Hoekstra et al., 2011). Green water (rainfall) accounts for over 90% of the water used in extensive grazing systems (Gerbens-Leenes et al., 2013), but climate,

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agricultural practices, and degree of extensivity of these systems are responsible for considerable variation in water use efficiency (Mekonnen and Hoekstra, 2012). International markets are increasingly concerned with the environmental impacts of animal products, and are willing to pay premium prices under some conditions, if there is evidence of reduced ecological footprints (Zonderland-Thomassen et al., 2014). Water footprint is developing into an important index of these impacts, and if adequately documented, it may evolve into a differentiating trait of agricultural products. Dourte et al. (2014) describe a web-based tool that allows estimation of the water footprint of various agricultural products in different regions of USA. Zonderland-Thomassen and Ledgard (2012) compared two methodologies for the estimation of the water footprint of milk production in two regions of New Zealand whereas the effects of climate change on animal production has been studied with a variety of models (Cullen et al., 2009; Graux et al., 2011; Sommer et al., 2013; Bocchiola, 2015; Chun et al., 2016). Nevertheless, the effects of climate and management on the water footprint of animal production are poorly documented (Nana et al., 2014; Palazzoli et al., 2015).

Assessments of water footprints in sheep systems are scarce. Mekonnen and Hoekstra (2012) estimated the water footprint of various animal products in different production systems, including that of extensive sheep systems, using secondary data such as herd numbers, number of animals slaughtered, yearly animal production and volumes of concentrate feed, derived mainly from FAO (2009). Chatterton et al. (2010) calculated the water footprint of beef and lamb in England using two simulation models (Water simulation model Wasim, and the Cranfield Life Cycle Assessment model). Elizalde (2013) estimated that the water footprint of extensive sheep production based on native rangelands in Western Patagonia of Chile amounted to 803,604 L·kg^{-1} carcass, 99.9% of which was green water.

Climate change affects Central Chile, and it has been predicted that rainfall will decrease and become more erratic (Neuenschwander, 2010; Zhang et al., 2013). In this context, the quantification of the current sheep water footprint constitutes a benchmark measure of water use efficiency, useful in estimating future proposed systems modifications vis-à-vis scenarios of climate change. The objective of the present study was to estimate the water footprint of extensive lamb production in Central Chile using a dynamic and stochastic simulation model to determine the effects of annual rainfall, adjustments in farmer-managed stocking rates and levels of supplementation, on the total water footprint, its partitioning into green-blue-grey water as well as tradeoffs in the use of physical outputs.

2. Materials and methods

2.1. Study region and production systems

Central Chile extends between latitudes 32° S and 36° S, plus patches around 46–47° S (Moreira-Muñoz, 2011; Silva and Acevedo, 2011). Average annual temperature is 13.5 °C, with the warmest month averaging 20.5 °C and the coolest 7.3 °C (Aguilar et al., 2006). The valleys and flatlands are dedicated to intensive, irrigated, horticulture, viticulture and pomology, whereas hilly lands are typically dominated by a woody savanna (Moreira-Muñoz, 2011). Farms are largely in the hands of family farms whose main source of income is meat sheep raised in extensive systems. These drylands, degraded by decades of cereal mono cropping (Brunel et al., 2011), are covered by low yielding, naturalized annual pastures (Ovalle and Squella, 1996). The rainy period lasts 2–4 months, with extremely variable yearly and monthly rainfall (Fig. 1).

The majority of the naturalized grasslands are degraded and low yielding, averaging 1000–2500 kg DM·ha^{-1}·year^{-1} (Ovalle and Squella, 1996). Sheep production is extensive, grazing is generally continuous, and on average grasslands cover 30% of the land area, interspersed with winter cereals and pine and eucalyptus plantations (INE, 2007). Nevertheless, grasslands and rangelands in family farms tend to represent larger percentages of the total farm area (averaging 64%). Cereal stubbles on average cover 3% of the farm area (Toro-Mujica et al., 2015) and are grazed during the dry period as reported for similar regions in Spain (Caballero and Fernandez-Santos, 2009). Cereals not harvested for grain due to deficient winter rainfall are conserved as hay for later use in summer. Merino or Suffolk sheep are mostly kept by family farms (ODEPA, 2013), stocked at <2 sheep·ha^{-1}. Ewes are mated during the dry months of December and January, to allow sale of lambs during September where demand is highest. Animals are grazed year-round without nighttime housing. Field observations show that suckling lambs are kept until reaching 25–35 kg live weight (LW) at 3–5 months of age at the beginning of the spring. Recorded lamb weights are lower in Merino sheep than in meat breeds such as Suffolk.

2.2. Estimation of the water footprint

2.2.1. Limits of the systems

The FAO (2010) cradle-to-farm-gate methodology was used to define the systems boundaries, so that the yearly use of water for all

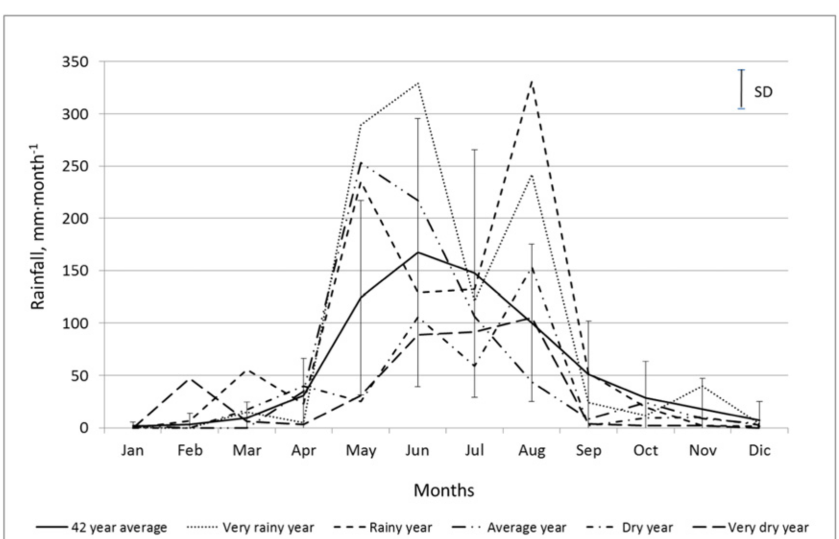

Fig. 1. Monthly rainfall of selected years, 43 year average and its standard deviation.