Replication of the *SequiaBasalto* model

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ODD protocol

1. Model description and purpose

This is a replication of the *SequiaBasalto* model, originally built in *Cormas* by Dieguez Cameroni et al. (2012, 2014, Bommel et al. 2014 and Morales et al. 2015). The model aimed to test various adaptations of livestock producers to the drought phenomenon provoked by climate change. For that purpose, it simulates the behavior of one livestock farm in the Basaltic Region of Uruguay. The model incorporates the price of livestock, fodder and paddocks, as well as the growth of grass as a function of climate and seasons (environmental submodel), the life cycle of animals feeding on the pasture (livestock submodel), and the different strategies used by farmers to manage their livestock (management submodel). The purpose of the model is to analyze to what degree the common management practices used by farmers (i.e., proactive and reactive) to cope with seasonal and interannual climate variations allow to maintain a sustainable livestock production without depleting the natural resources (i.e., pasture). Here, we replicate the environmental and livestock submodel using *NetLogo.* In the future, we will use this replication to conduct new simulations and evaluate the role of different management strategies for adapting to climate change.

2. Entities, state variables, and scales

The entities of the model are cows and patches with grass. Although the original model is not spatially explicit, this replication includes patches of 1 hectare each that are connected to each other. Therefore, the world represents one “wrapped” homogeneous paddock in terms of grass availability and quality, and with no divisions, where the size (i.e., number of patches) is determined by the observer.

Agents are cows. A healthy British breed herd was assumed, without predators, with a 2% natural annual mortality and the possibility of exceptional deaths due to forage crisis when animal Live Weight (LW) falls below a critical survival value (i.e., Minimum Weight). In this study system, an Animal Unit (AU) is defined as a cow with an LW of 380 kg. The AU is a common concept in grazing management that aims to determine proper stocking rates in specific environments standardizing the impact of livestock, focusing mainly on the effects of forage demand (estimated intake). The time step of the model is one day.

The values of the variables and parameters used in this model are shown in Table 1.

Table 1. *List and description of variables and parameters*

Entity	Variable	Description	Value	Unit
Patch	Climacoef	Affects the grass growth.	0.5 – 1.5	-
	DM-cm-ha	Quantity of dry matter contained in one centimeter per hectare.	180	kg/cm/ha
	GrassEnergy	Grass metabolizable energy content in one kilogram of dry matter.	1.8	Mcal/kg
	Grass-height (GH)	Primary production (biomass), expressed in centimeters.	1 – 22.2	cm
	Kmax (K)	Carrying capacity. Is the maximum grass height achieved according to the season of the year.	Winter = 7.4 Spring = 22.2 Summer = 15.6 Fall = 11.1	cm
	r	Maximum growth rate of grass.	0.02	$days^{-1}$
Cattle	Age	Age of each animal.	0 - 5520	days
	Categcoef	Affects the grass consumption of animals.	See Table 2	-
	CoefA	Affects the pregnancy rate of animals.	See Table 2	-
	CoefB	Affects the pregnancy rate of animals.	See Table 2	-
	Cow-age-max	Life expectancy of cattle (i.e., when the animal reaches 5520 days, it dies)	5520	days
	Cow-age-min	This variable, together with a minimum weight of 280 kg, determines the beginning of the “cow” stage for heifers (i.e., when the animal reaches 737 days of age AND 280 kg, it enters the “cow” age class)	737	days
	Daily Dry Matter Consumption (DDMC)	Amount of grass (in kg) consumed by cattle.	See Equation 3	kg
	Gestation-period	Duration of the gestation period of pregnant cows.	276	days
	GH-consumed	Grass height (in cm) consumed by all animals.	See section 3.4	cm

	GH-individual	Grass height (in cm) consumed per animal.	See section 3.2	cm
	Heifer/steer-age-min	Beginning of the “heifer” (for female calves) or “steer” (for male calves) stage of the livestock life cycle (i.e., when the “weaned-calf" reaches 369 days of age, it enters the “heifer” or “steer” age class)	369	days
	Lactating-time	Determines the lactating period of cows with calves.	246	days
	Live-weight (LW)	State of the animals in terms of live weight. The initial live-weight is defined at the start of simulation.	40 – 1500	kg
	Live-weight-gain (LWG)	Increment of weight.	See Equation 2	kg
	MaxLWG (μ)	Maximum live weight that cattle can gain according to the season of the year.	Winter = 40 Spring = 60 Summer = 40 Fall = 40	kg
	Ni (ν)	Affects the live weight gain of cattle.	0.24	cm^{-1}
	Pregnancy-time	Gestation period of pregnant cows.	276	days
	Seasoncoef	Affects the live weight gain in relation with the grass quality (determined by the season of the year).	Winter = 1 Spring = 1.15 Summer = 1.05 Fall = 1	-
	Weaned-calf-age-min	Beginning of the “weaned-calf” stage of the livestock life cycle (i.e., when an animal within the “born-calf” age class reaches 246 days of age, it enters the “weaned-calf” age class)	246	days
	Weight-gain-lactation	Live weight gain of lactating animals (i.e., “born-calf” age class).	0.61	kg
	Xi (ξ)	Affects the live weight gain of cattle.	132	kg

3. Process overview and scheduling

One year is 368 days. Seasons change every 92 days. Each day begins with the growth of grass as a function of climate and season. This is followed by updating the live weight of cows according to the grass height of their patch, and grass consumption, which is determined based on the updated live weight. After consumption, cows grow and reproduce, and a new grass height is calculated. Cows then move to the patch with less cows and with the highest grass height. This updated grass height value will be the initial grass height for the next day.

The main procedures are shown in Figure 1 and are explained in detail in the following sections.

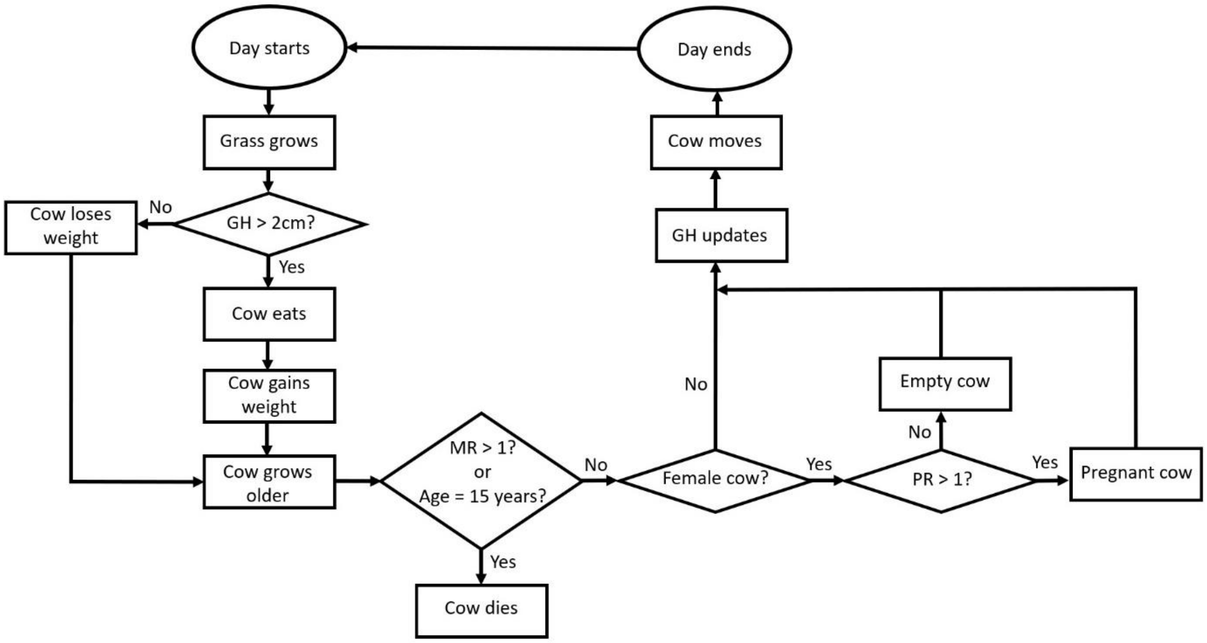

***Figure 1**. Flow chart of the model during one day. Abbreviations: GH, grass height; MR, mortality rate; PR, pregnancy rate.*

3.1. Grass grows

The grass grows following a logistic regression. Thus, Grass Height (GH) is:

(Eq. 1) $GH = GH_{to} + GH_{to} \times r \times \left(1 - \frac{GH_{to}}{K\ x\ Climacoef}\right)$ - $GH\text{-}consumed$

Where *K* is the maximum GH, *Climacoef* is the climate coefficient, *GHt0* is the initial GH, *r* is the growth rate of grass, *t* is the time (day) and *GH-consumed* is the amount of grass height, in centimeters, consumed by cattle.

The value of *K* varies every 92 days, when the season changes (Table 1). *Climacoef* takes values from 0.5 to 1.5 representing a “low production” (below the average = 0.5 – 0.9), a “normal production” (equal the average = 1), and a “high production” (above the average = 1.1 - 1.5).

3.2. Cows eat grass and gain weight

When cows eat grass, they gain weight. This live weight gain (LWG) depends on the season of the year and the GH, following the equation:

(Eq. 2) $LWG = \frac{\mu - \left(\xi \times e^{-v \times GH-individual}\right)}{92\ \times Seasoncoef}$

Where μ is the maximum LWG (Table 1), ξ and v are constants (Table 1), *GH-individual* is the amount of grass, in centimeters, that corresponds to each cow, 92 is the length of a season in days, and *Seasoncoef* is the seasonal coefficient (Table 1).

When two or more cows are in the same patch (i.e., in a hectare), the resource is shared among the number of agents within that patch. Cows only eat when the GH of the patch is equal or more than two centimeters. Cows in a patch with less than two centimeters of GH loss 0.5% of their LW. Born calves, not dependent on grass, increase their initial LW of 40 kg by 0.61 Kg per day.

The grass consumption (*DDMC*, daily dry matter consumption) is calculated following the equation:

(Eq. 3) $$DDMC = \frac{[0.107 \times MBS \times (-\ 0.0132 \times GH{-}individual + 1.5132) + (0.141 \times MBS \times LWG)]}{GrassEnergy} \times Categcoef$$

Where *MBS* is the metabolic body size (LW $^{3/4}$), *GrassEnergy* is the grass metabolizable energy content (1.8 Mcal/Kg DM), and *Categcoef* is a coefficient that varies with the age class of cows (Table 2).

3.3. Cows grow, reproduce, and die

Cows are divided into six groups of age: born calf, weaned calf, heifer or steer, cow, and cow with calf (Figure 2). Table 2 shows the attributes of each group of age.

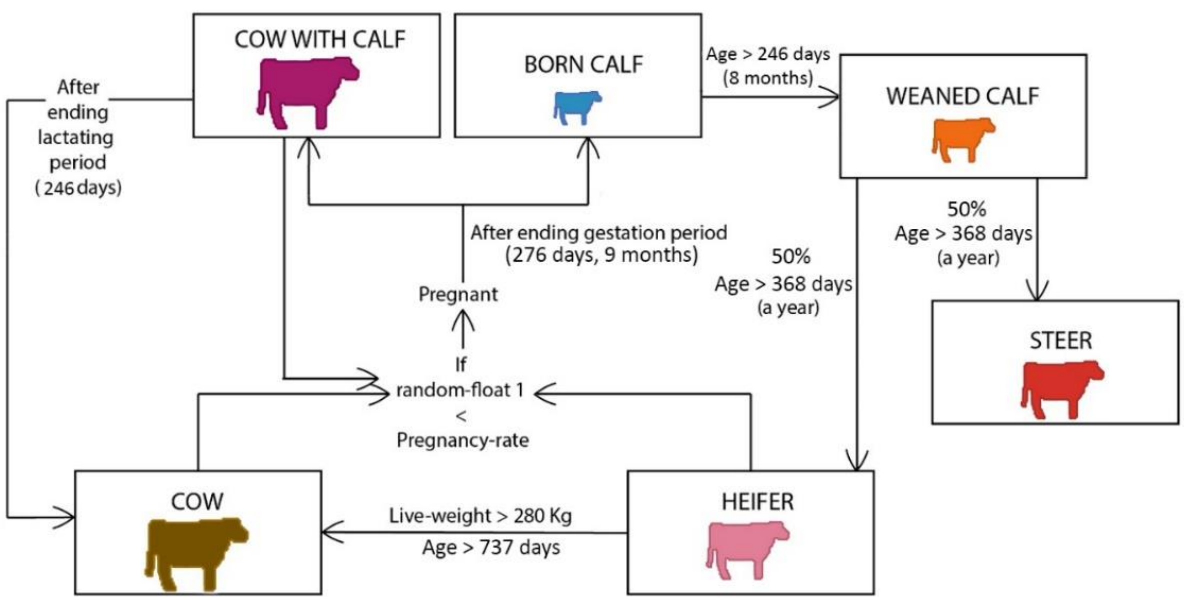

***Figure 2**. Diagram of age classes.*

Heifers, cows and cows with calves can reproduce. Their pregnancy rate follows a logistic equation and depends on LW:

(Eq. 4) $$Pregnancy\ rate = \left(\frac{1}{1 + CoefA \times e^{-\ CoefB \times LW}}\right) : 368$$

Where CoefA and CoefB are coefficients that varies with age class and affects the pregnancy rate of animals. (Table 2).

Gestation period lasts 276 days, and lactating period lasts 246 days.

The daily mortality rate of cows (5.4×10^{-5}) increases (i.e., exceptional mortality rate) when LW is under a critical weight (i.e., minimum weight) (Table 2).

***Table 2**. Attributes of cows by age class.*

Age class	Animal units (AU)	Initial weight (kg)	Minimum weight (kg)	Exceptional mortality rate (%)	Category coefficient (categCoef)	CoefA	CoefB
Cow	LW/380	-	180	15	1	20000	0.0285
Cow with calf	LW/380	-	180	30	1.1	12000	0.0265
Born calf	LW/380	40	-	0	1	-	-
Weaned calf	LW/380	-	60	23	1	-	-
Heifer	LW/380	-	100	23	1	4000	0.029
Steer	LW/380	-	100	23	1	-	-
Pregnant?	LW/380	-	180	30	1	-	-

3.4. Post-consumption grass height and movement of cows

Using the local variable “totDDMC”, the total DDMC in each patch is calculated. With the parameter “DM-cm-ha”, which defines that each centimeter per hectare contains 180 Kg of dry matter, the GH consumed in each patch can be calculated.

At each daily time step, the height of pasture offered to the animals (pre-consumption height) will be the result of the initial daily height plus the daily growth. The post-consumption height (difference between pre-consumption height and consumption in cm of pasture) of one day will be the initial height of the following day. Therefore, we update the GH subtracting the GH consumed from the current GH.

After the grass height update, cows can move through the world, looking for more pasture to consume. Cows move to the patch with less cows and with the highest GH.

4. Design concepts

Emergence: the main outputs of the model are the stocking rate, live weight and pregnancy rate of the animals, and the resource level of the system over time. These outcomes emerge from the interactions between the livestock submodel (animals feeding on the resource) and the environmental submodel (grass growth as a function of climate and seasons).

Adaptation: agents do not actively adapt.

Objectives: The fitness measure of the agents is their live weight. If the live weight is below a critical threshold (Table 2), the mortality rate of the agent increases exceptionally. If this mortality rate is greater than 1, the agent dies. The reproductive capacity of agents (i.e., the pregnancy rate) is directly related to the live weight of the agent. Agents have a fixed set of rules that determine what they do given the context of their environment. Agents move to the patch with fewer cows and with the highest grass height.

Learning: agents do not learn.

Prediction: agents do not make predictions.

Sensing: agents sense the number of animals and the resource level of every patch in the system, including the patch they are on.

Interaction: the level of resource in the system depends on the seasons and the climate scenario. Animals interact directly with patches by feeding on the resource, and indirectly with each other by consuming the resource from the landscape.

Stochasticity: stochasticity affects the normal mortality rate of animals (the daily mortality rate of cows is 5.4×10^{-5}). Slightly stochastic processes also affect exceptional mortality and pregnancy rates, although these parameters are mostly determined by the live weight of the animals.

Collectives: animals are divided into six groups of age (Figure 2): born calf, weaned calf, heifer or steer, cow, and cow with calf. Each of these groups has different thresholds for the same parameters, such as mortality rate, minimum live weight, pregnancy rate, and amount of grass consumed at each stage (Table 2).

Observation: we observe the emergent population (population dynamics by age class and stocking rate) and resource levels (average grass height, total dry matter and dry matter consumption), as well as the live weight, body condition and pregnancy rate of the animals. Other outcomes provided are crop efficiency (dry matter consumed / dry matter offered) and average live weight gain over a season and over a year.

5. Initialization

Simulations are initialized in *winter*, in a *business-as-usual* climate scenario (i.e., climate coefficient = 1), with 50 adult empty cows grazing freely on a landscape of 100 ha. Cows initialize with a random age within their age range (737 - 5520 days) and an *initial live weight* of 380 kg. Patches start with an *initial grass height* of 7.4 cm. The simulation run for 10 years (each simulation can run from 1 to 100 years).

Users can use the sliders at the interface to determine: 1) the size of the grazing area (from 1 to 10000 ha); 2) the initial GH (from 1 to 22.2 cm); 3) the initial season (0 = *Winter*, 1 = *Spring*, 2 = *Summer*, and 3 = *Fall*); 4) the climate coefficient (1.5 = "*high production*", 1 = "*normal production*", 0.5 = "*low production*"); 5) the initial number of cows (from 0 to 1000); 6) the initial LW of cows (from 100 to 1500 kg); 7) the initial number of steers (from 0 to 1000); and 8) the initial LW of steers (from 100 to 1500 kg).

6. References

Dieguez Cameroni, F.J., Terra, R., Tabarez, S., Bommel, P., Corral, J., Bartaburu, D., Pereira, M., Montes, E., Duarte, E., Morales Grosskopf, H., 2014. Virtual experiments using a participatory model to explore interactions between climatic variability and management decisions in extensive systems in the basaltic region of Uruguay. *Agricultural Systems.* 130, 89– 104. http://dx.doi.org/10.1016/j.agsy.2014.07.002

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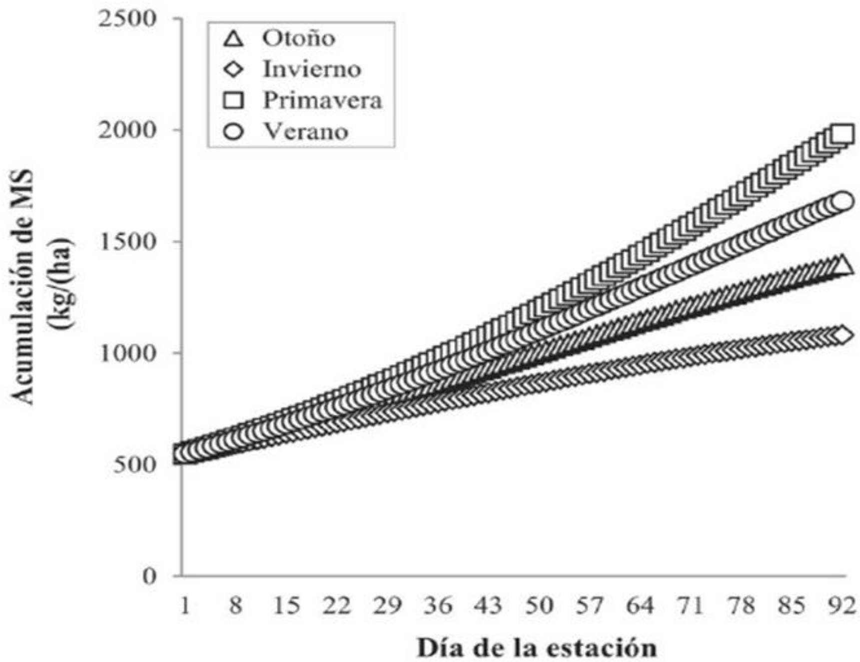
7. Implementation

Below we compare the *NetLogo* simulations with the results of the original model (Dieguez Cameroni et al., 2012).



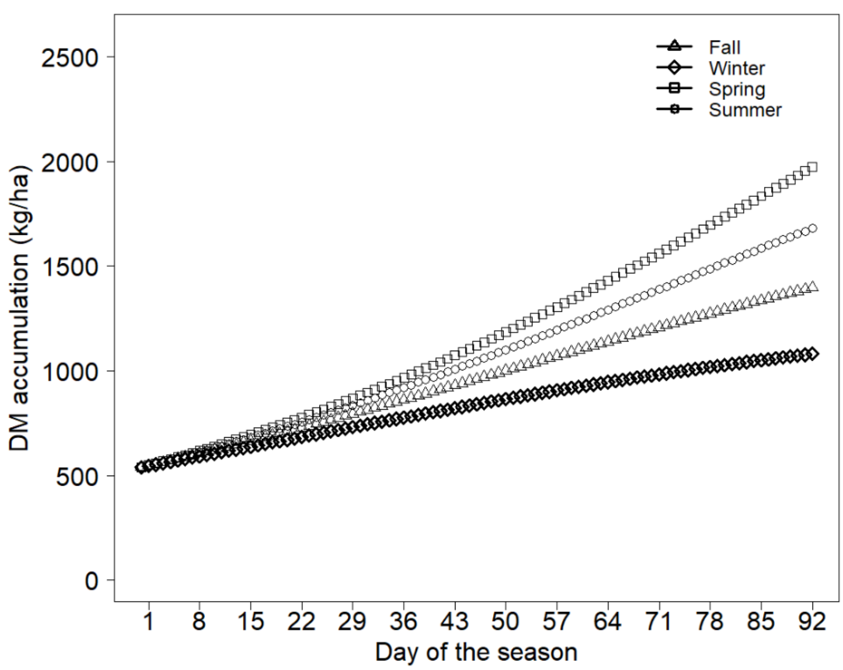


Figure 3. Evolution of dry matter (DM) availability by season, for a simulation without animal consumption and with average dry matter growth rate (DMGR) conditions, using an initial grass height of 3 cm. Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

Table 3. Comparison of accumulated DM, distribution, and average DMGR, for one simulation, with no animal consumption and with average DMGR conditions, using an initial grass height of 3 cm in each season. Top: original table by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

		Fall	**Winter**	**Spring**	**Summer**	**Total**
Dieguez Cameroni et al., (2012)	DM accumulated (kg DM/ha)	851	535	1433	1133	3952
	Distribution (%)	22	14	36	29	100
	DMGR (kg DM/ha/day)	9.3	5.9	15.7	12.4	
SequiaBasalto Netlogo	DM accumulated (kg DM/ha)	**858**	**541**	**1434**	**1141**	**3975**
	Distribution (%)	**22**	**14**	**36**	**29**	**100**
	DMGR (kg DM/ha/day)	**9.3**	**5.9**	**15.6**	**12.4**	

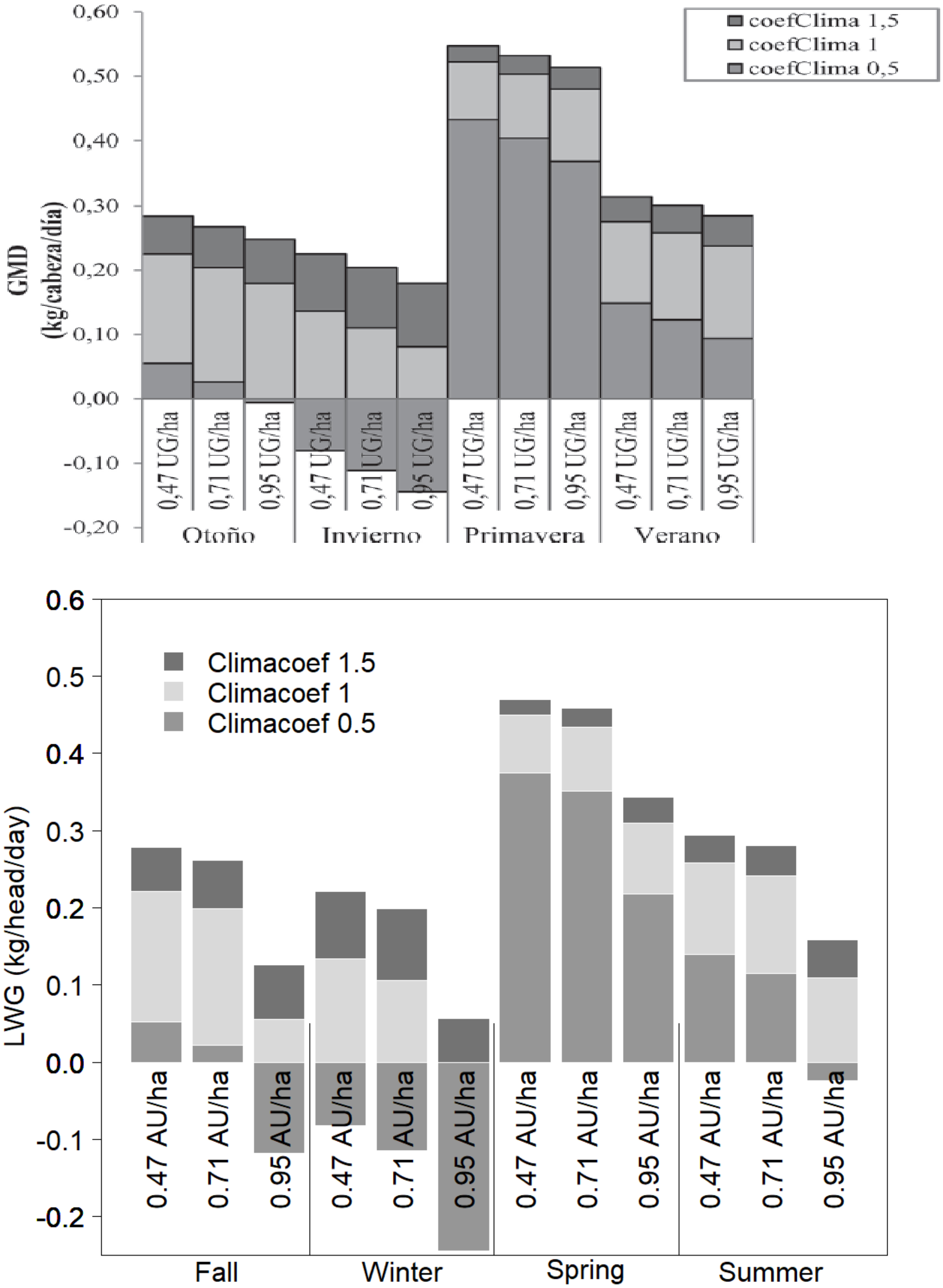


Figure 4. Average live weight gain (LWG) per season, considering three different Climacoef scenarios and three different initial stocking rates (SR). Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

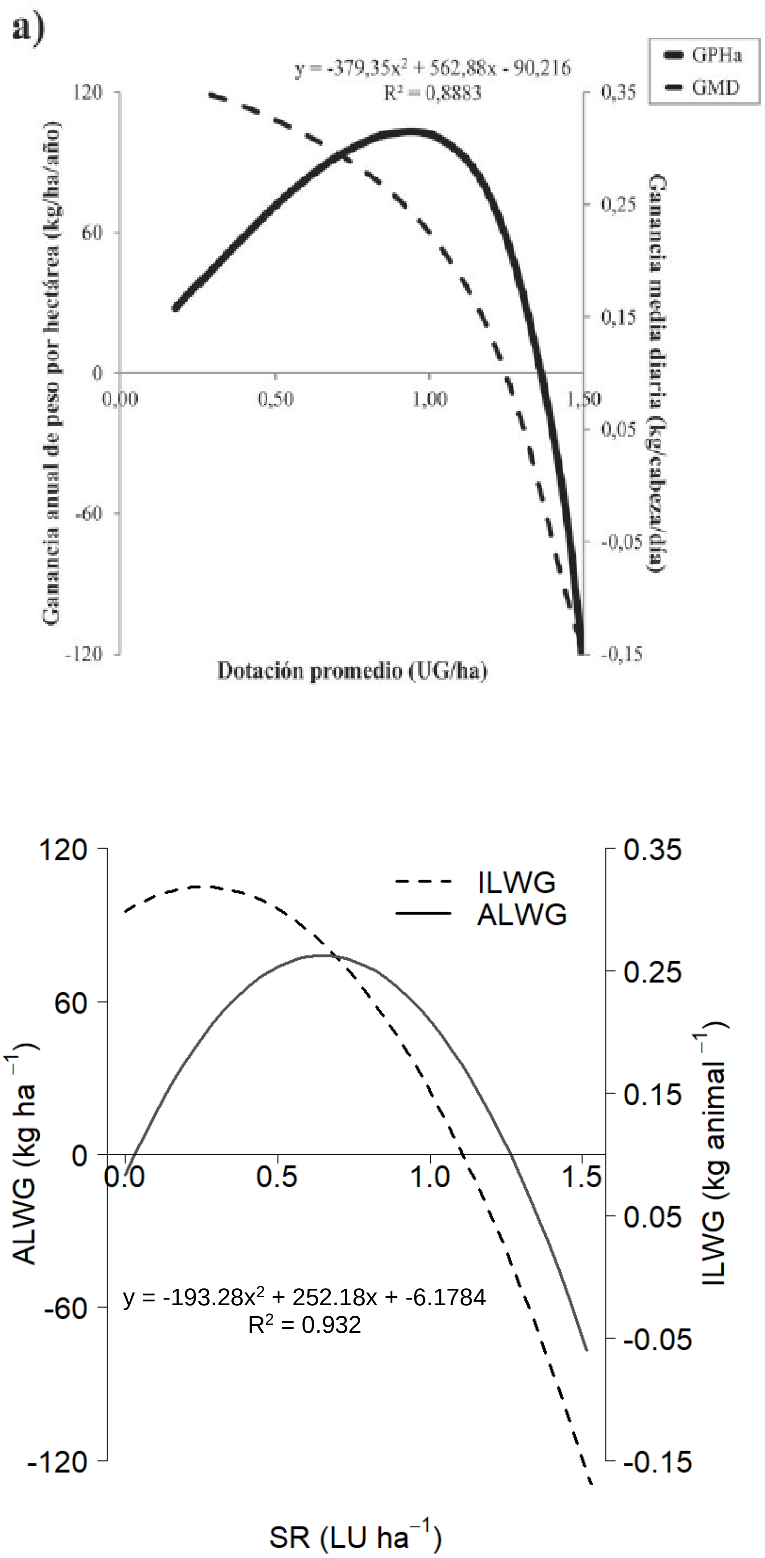


Figure 5a. LWG and Annual Live Weight Gain (ALWG) as a function of SR, for an average DMGR in all seasons (Climacoef = 1). Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

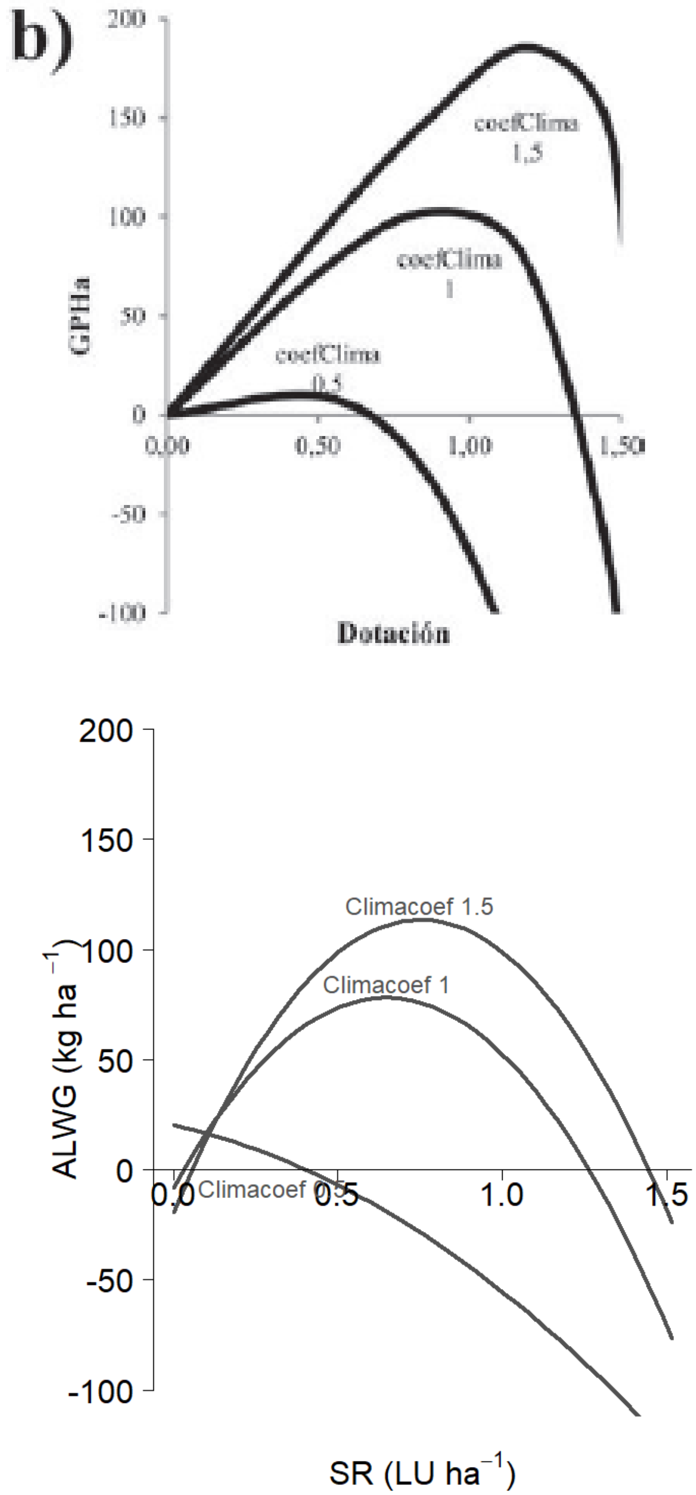


Figure 5b. ALWG for different simulations with different Climacoef. Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

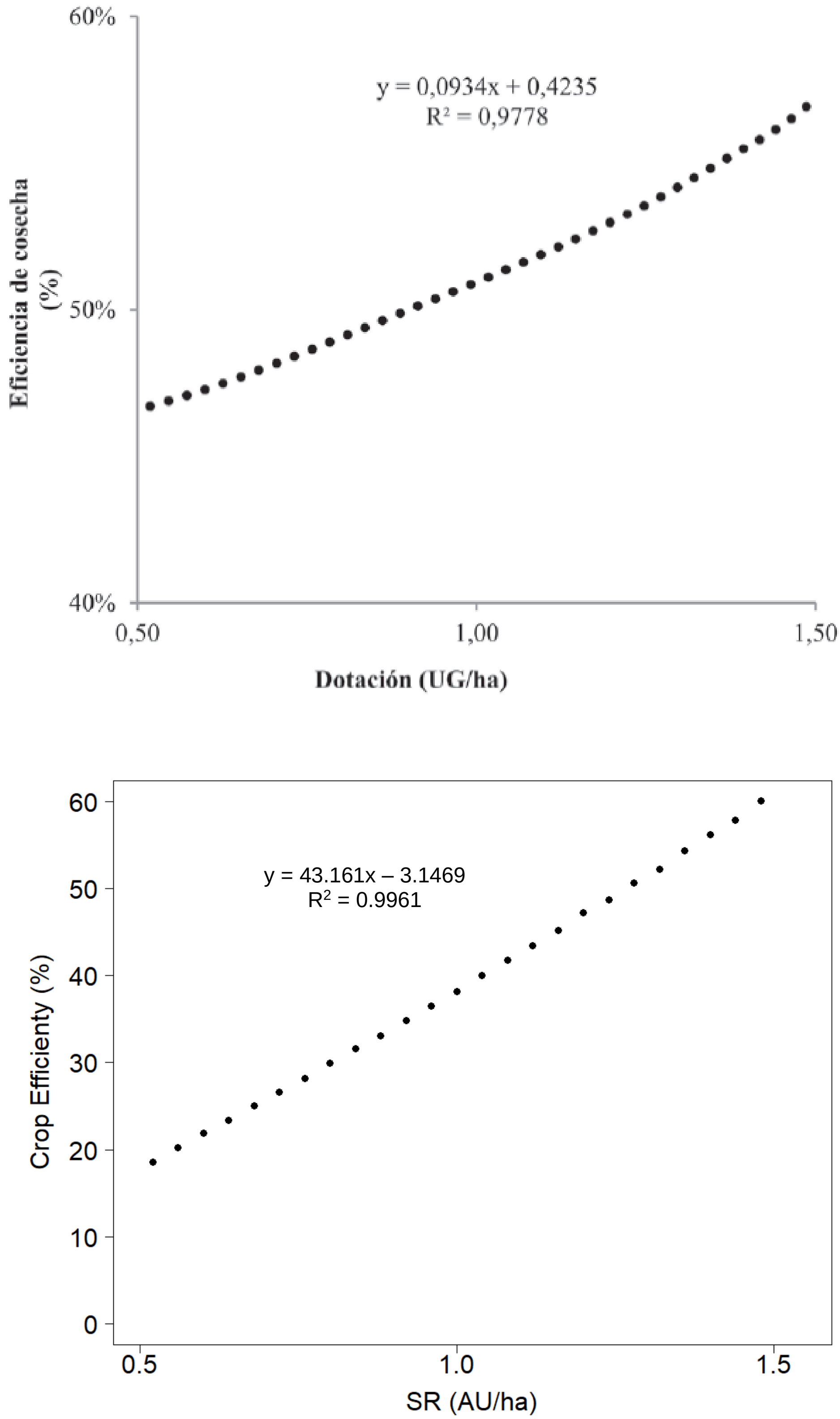


Figure 6. Crop efficiency (CE) as a function of SR. Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.

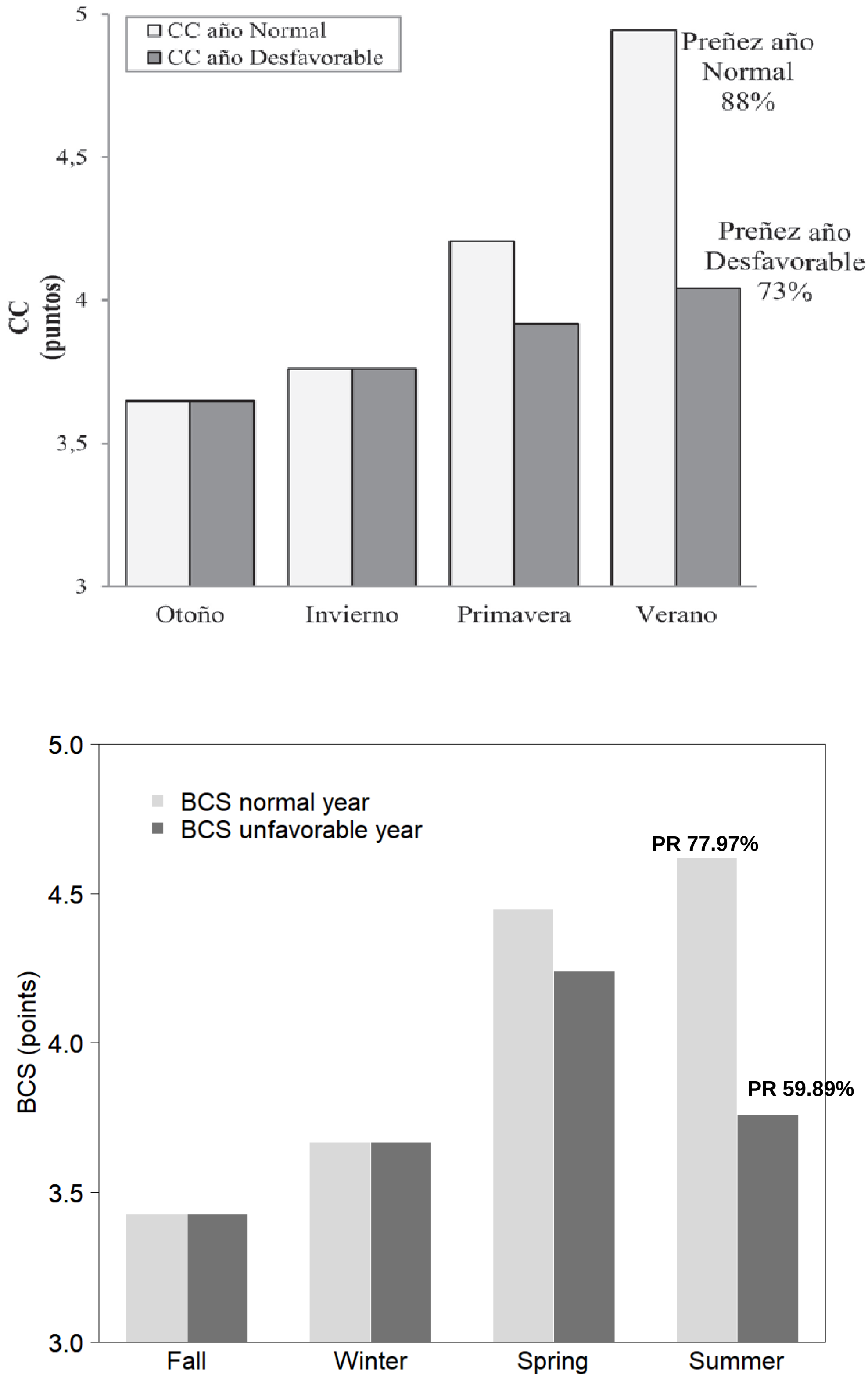
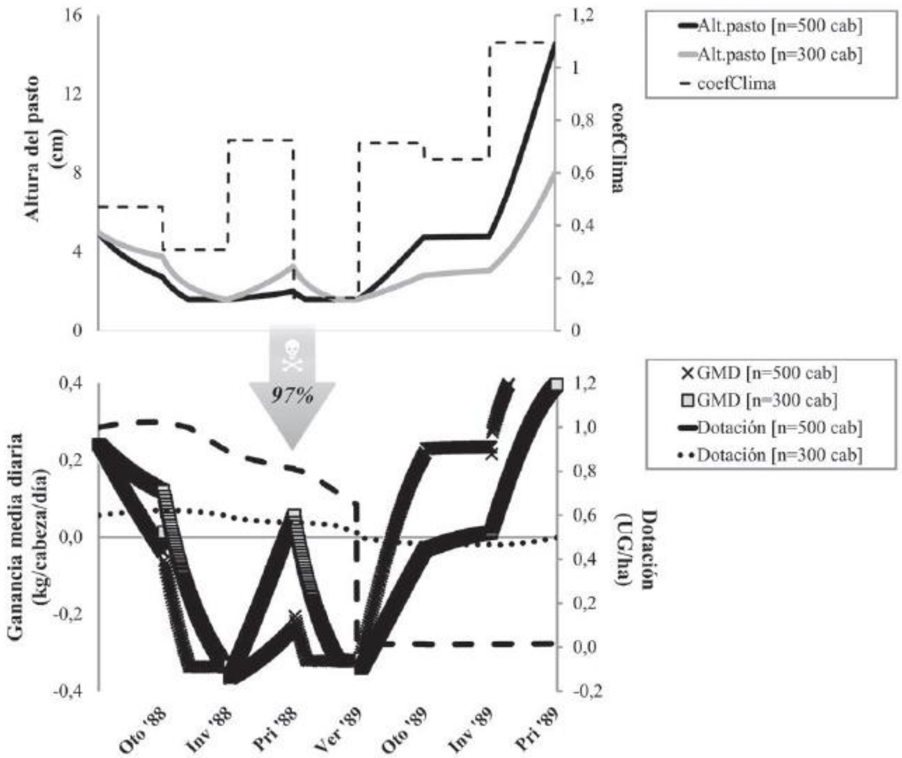


Figure 7. Body Condition Score (BCS) and Pregnancy Rate (PR) for two simulations: a "normal" year and an "unfavorable" year. Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.



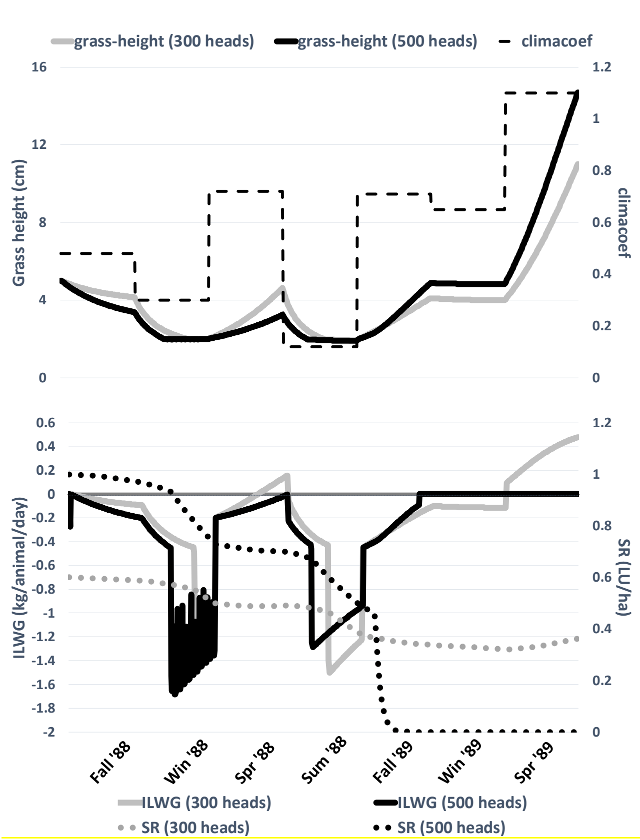


Figure 8. Simulation of the 1988-1989 summer drought. Top: original figure by Dieguez Cameroni et al. (2012), bottom: results of the *NetLogo* simulations.