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# Livestock Settlement Dynamics in Drylands: Model application in the Monte desert (Mendoza, Argentina)

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ABSTRACT

Human settlements in arid environments are becoming widespread due to population growth, and without planning, they may alter vegetation and ecosystem processes, compromising sustainability. We hypothesize that in an arid region of the central Monte desert (Mendoza, Argentina), surface and groundwater availability are the primary factors controlling livestock settlements establishment and success as productive units, which affect patterns of degradation in the landscape. To evaluate this hypothesis we simulated settlement dynamics using a Monte Carlo based model of Settlement Dynamics in Drylands (SeDD), which calculates probabilities on a gridded region based on six environmental factors: groundwater depth, vegetation type, proximity to rivers, paved road, old river beds, and existing settlements. A parameter sweep, including millions of simulations, was run to identify the most relevant factors controlling settlements. Results indicate that distances to rivers and the presence of old river beds are critical to explain the current distribution of settlements, while vegetation, paved roads, and water table depth were not as relevant to explain settlement distribution. Far from surface water sources, most settlements were established at random, suggesting that pressures to settle in unfavorable places control settlement dynamics in those isolated areas. The simulated vegetation, which considers degradation around livestock settlements, generally matched the spatial distribution of remotely sensed vegetation classes, although with a higher cover of extreme vegetation classes. The model could be a useful tool to evaluate effects of land use changes, such as water provision or changes on river flows, on settlement distribution and vegetation degradation in arid environments.

## 1. Introduction

Livestock production, the largest land use sector on Earth, is experiencing changes related to climate change and anthropogenic pressures. Population and economic growth, urbanization, and consumption patterns are shaping livestock production, with impacts on societies and environments, such as greenhouse gas emissions, nutrient cycles, land demand and degradation, and protein supply (Herrero and Thornton, 2013). The challenge to feed the world sustainably partly depends on how we understand and manage the livestock sector. In drylands, which sustain a third of the world population and 78 % of livestock worldwide (Asner et al., 2004; Corvalan et al., 2005), livestock production is one of the main economic activities. Groundwater coupled ecosystems in the Monte desert (Argentina) are used for subsistence livestock production, which allows the coexistence of areas with high vegetation cover in most of the region (Goirán et al., 2012), and rural communities. However, changing land rights, water provision, infrastructure, and population growth may increase population density and grazing pressures, with increasing risks of ecosystem degradation. In order to predict future conditions of livestock production and ecosystems in the region, it is crucial to understand the feedbacks between natural resources and livestock settlements at present.

Several models have been used to understand and simulate settlement dynamics in different regions of the world. Settlement Dynamics has been simulated using Agent-based models (ABM) in Kohler et al. (2012) and Crabtree and Kohler (2012), also using Multi-Agents in Bura et al. (1996) and Le et al. (2008, 2010), using Knowledge-based simulations in Page et al. (2001) and with decision making rules for land cover changes in the Amazon in Evans et al. (2001). Dispersion of plants has been simulated with stochastic models based on environmental conditions relevant for their survival

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in Fennell et al. (2012). In this work, we use a novel approach to simulate settlement dynamics (Millán et al., 2016), which allows to spatially consider vegetation-human interactions, with a probabilistic model.

Several factors may influence the dynamics of livestock settlements in arid environments, including environmental and socioeconomic drivers. Availability of forest resources, groundwater, and access roads may all affect settlement patterns, but their interactions or relative importance on settlements distribution and success are not known. Goirán et al. (2012) studied the spatial distribution of human settlements in North East (NE) Mendoza, finding a heterogeneous pattern, with spatial aggregations around rivers and other landscape features, indicating the importance of water availability for settlements. However, the relative importance of surface, groundwater, and old river beds is difficult to obtain from a simple observation of settlement distribution, because more than one factor may have opposing or multiplying effects on a given space. Goirán et al. (2012) also found a pattern of concentric vegetation reductions around settlements, given by the concentration of animals and higher pressures around water points, also observed in other deserts (Ringrose et al., 1996). The practice of night-time livestock accumulation, free grazing around settlements, and the scarcity of permanent fresh water sources generate concentric gradients of grazing pressure. Because environmental and economic changes may encourage or discourage settlement establishment and change their distribution in the landscape, we aim to identify the main drivers of landscape occupation in these arid groundwater-coupled ecosystems. We hypothesize that surface and groundwater availability are the most important factors for settlements in drylands, and forest resources and access roads have a minor effect.

In order to test this hypothesis for the Monte desert, we used a Monte Carlo based model of Settlement Dynamics in Drylands (SeDD) (Millán et al., 2016), which supports different types of environmental factors. We included six environmental drivers of settlements: surface and groundwater availability, vegetation type, existing settlements, access routes, and old river beds. These factors provide different services to settlers, such as water provision for humans and livestock, forest products for construction and forage, transport and communication with existing settlements and other regions, and initial labor, materials, and water during the construction period. The model assumes that places with higher availability of water and forest resources will be preferentially settled, independently of the social structure. The model assigns settlements in places where the aptitude (simulated as probabilities) is higher, with a number of settlements established stochastically. The model simulates the number and distribution of settlements from 1928 to 2015. The model also simulates the degradation of vegetation around settlements, gradually reducing the suitability of these spaces. Vegetation degradation around settlements is simulated up to 2 km, according to observed vegetation patterns in the region (Goirán et al., 2012). Our model differs from plant and animal dispersion models (i.e., Fennell et al., 2012) because it assumes that settlers have a prior knowledge of the environment in the entire region, simulating environmentally-based, human informed decisions. Millions of simulations with combinations of crucial parameters were run to find minimum residuals between simulated and observed spatial indexes of settlements in relation to other settlements, rivers, and roads. Combinations of parameter values that resulted in low residuals were interpreted to indicate the relative importance of each parameter.

The simulations performed suggest that environmental factors related to surface water availability (river and old river beds) are the most important to settlers. The presence of a paved road does not seem to influence the decision of establishing new settlements. Finally, groundwater and vegetation do not change settlement distribution considerably.

## 2. Materials and methods

### 2.1. Study area description

Our study area is located in the non irrigated lands of North East Mendoza, Argentina, where mean annual precipitation is below 200 mm. The region is framed by permanent and temporary rivers (San Juan, Desagüadero, Mendoza, and Tunuyán rivers). Groundwater is recharged in the Andes (100 km west) and reaches the area with a high salt and arsenic content, preventing its use for irrigation (Aranibar et al., 2011). The region has an aeolian plain with sand dune-interdune systems, old river beds, and lacustrine systems (Fig. 1), with varying access to surface and groundwater. Most of the region is occupied by the aeolian plain, and lacks surface water. One of the four old river beds of the region crosses the aeolian plain from West to East, providing an easier access to the territory, and localized patches of groundwater with a better quality (Aranibar et al., 2011; Jobbágy et al., 2011). The other old river beds are shorter, and interrupted by sand dunes. Historic documents suggest that river beds have been dried at least from 1778 (Prieto, 1997). The only paved road of the region (road Number 142) was built along the main old river bed for most of its length. People live in livestock settlements, which mostly hold 1 to 3 families (from 1 to 10 persons) and their livestock (mainly goats, but also cattle and horses) with an average size of 160 (Soria et al., 2011). At present, there are 577 settlements with a heterogeneous spatial distribution, aggregated at different scales (Goirán et al., 2012). Settlements located far from the paved road are accessed through dirt roads that cross the high sand dunes of the aeolian plain, decreasing the possibilities of communication, trade, and transportation between areas.

In interdune valleys where groundwater is near the surface (from 5 to 15 m depth), highly productive, phreatophyte, *Prosopis flexuosa* forests develop (Contreras et al., 2011; Jobbágy et al., 2011). These forests have been seasonally used by aboriginal groups since pre-hispanic times, providing them with hunting animals and *Prosopis pods* (Llorca and Cahiza, 2007). During colonial times, many aboriginal (Huarpe) individuals or groups used the area as a refuge, changing the previous seasonal and complementary occupation of the area to a more permanent pattern of occupation (Escolar, 2007; Prieto, 1997). During the 19th century, part of the forests were cut for railroad and vineyard construction in irrigated oases, but sand dunes prevented clear cutting in certain areas, where old *Prosopis flexuosa* individuals still remain (Alvarez et al., 2006; Villagra et al., 2005).

At present, local Huarpe descendants still inhabit these lands, mainly practicing subsistence livestock production in permanent livestock settlements, which rely exclusively on groundwater for most uses. Animals graze freely during the day around the settlement, but return at the end of the day to drink water, and they are kept in corrals during the night. In areas close to paved roads, people have access to drinking water, transported from irrigated oases by trucks, or a recently (2012) built aqueduct. The hydrogeology of the region, including a shallow aquifer and fine sediments (Aranibar et al., 2011), allows the construction of wells by independent individuals at a relatively low cost, without government assistance. Wells are constructed near the corral and housing area with wooden *Prosopis flexuosa* frames, and groundwater is extracted manually, or with the help of an animal. This relative independence of livestock owners from government assistance and planning allows settlers to establish in areas that they consider appropriate for their subsistence, probably basing their decisions on their knowledge of natural resources availability, as we simulate with our model.

The exclusive reliance of livestock on groundwater from their settlements causes a pattern of night-time animal concentration around wells and corrals, as also observed in Botswana, Patagonia and other arid areas. This causes higher pressures near wells, and consequent changes on soils, groundwater quality, and vegetation

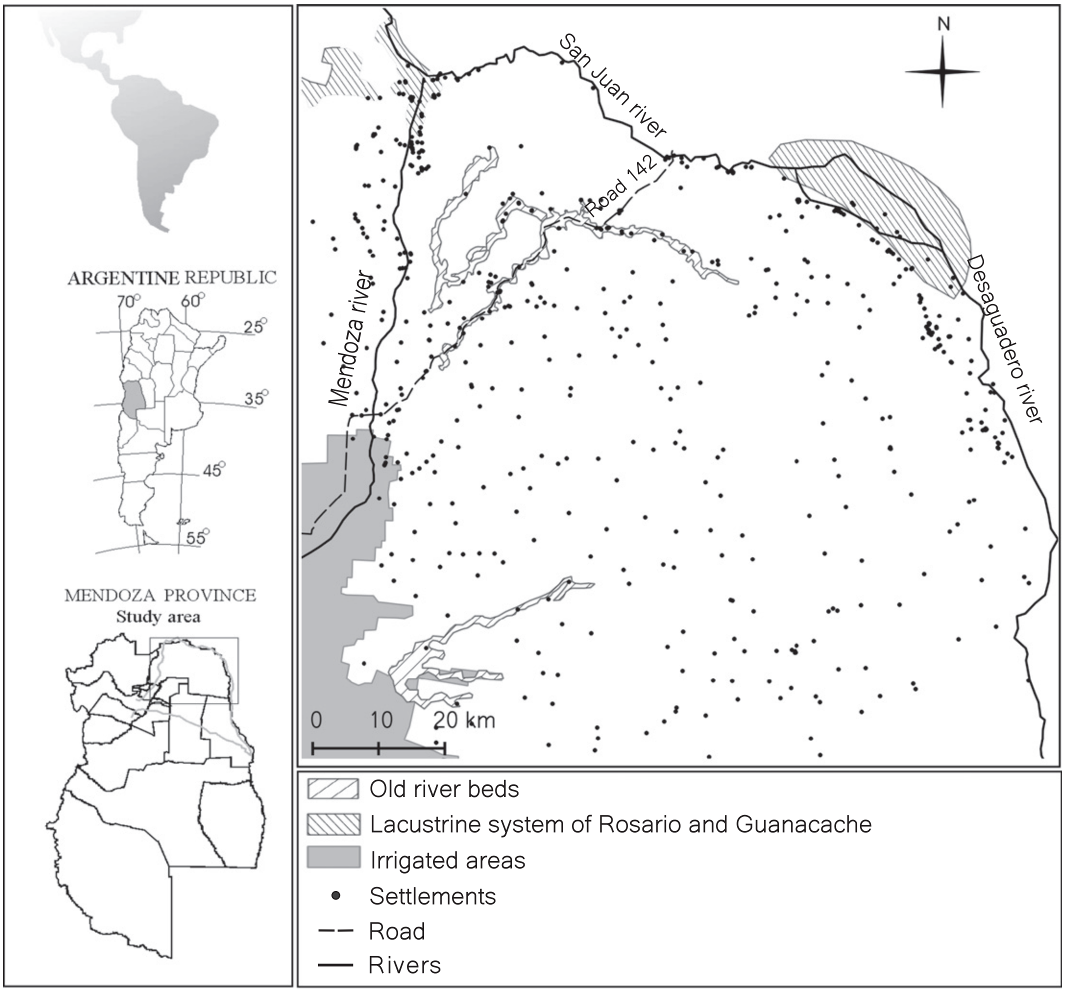

**Fig. 1.** Study area showing the aeolian plain (without filling), rivers, road, lacustrine systems, irrigated areas, old river beds, and settlements.

(Aranibar et al., 2011; Bisigato and Bertiller, 1997; Goirán et al., 2012; Meglioli et al., 2013; Ringrose et al., 1996). Most changes are visible in rings of 2 km around livestock settlements, although overlap of grazing areas with high settlement densities may cause vegetation reductions in larger areas (Goirán et al., 2012; Ringrose et al., 1996).

### 2.2. Modeling description for the Monte desert

We modeled settlement dynamics to test the hypothesis that natural resources, mainly water, play a determinant role on the decision to establish new livestock settlements, and their success as productive units. We simulate the aptitude or suitability of the landscape as probabilities for settlement, based on the partial probabilities given by different environmental conditions (Millán et al., 2016). We assumed that local inhabitants have a knowledge of certain environmental features in the whole region, so they are capable of settling in any place of the region that they consider appropriate (i.e., the model selects, at each time step, the pixel with maximum probability found in the whole area). Then, areas with a higher suitability (simulated as probability) will be preferentially settled. The model also has a stochastic component to assign a proportion of the settlements in unfavorable places at random, controlled by the parameters *Pset* and *Pthresh* (Table 1). We considered that rivers have a positive influence in settlements up to 5 km away, because animals can travel this distance to water sources. Shallow groundwater is the main water source for most settlements (including those close to rivers), which is extracted with manually built wells. For this reason, we include water table depth as a controlling factor for settlements.

Old river beds may also be preferential areas for settlement, because their smooth slopes and finer sediments than their surroundings allow rain water accumulation in soil ditches (*jagüels*), providing an additional, although temporal, freshwater source for domestic animals. Patches of groundwater with a better quality are found in old river beds, and the smooth and uniform slopes could provide an easier access and better communication to other areas, probably favoring settlement dispersion.

**Table 1**
Input parameters and values used in our simulations. Values marked in bold correspond to optimized values selected with the parameter sweep.

| Parameter | Description, unit | Value |
|---|---|---|
| dr | Width of the bin for the g(r) pair correlation function, pixels | 1.0 |
| Length | Side of grid, pixels | 150 |
| **Pset** | Being the minimum probability value to establish a settlement by high probability in a given pixel | 0.14 |
| Pthresh | Rejection threshold of total probability to place a settlement randomly | 0.85 |
| SettlementMax | Maximum number of established settlements | 10,000 |
| TimeminSet | Minimum time between established settlements, time steps | 1 |
| TotalSteps | Number of time steps that the simulations run | 2000 |

Roads provide clear advantages to settlers, including a better access to commercialization centers and irrigated agricultural areas, where people often work during the harvest season. Fresh water is also transported from the oases in trucks, but they only reach accessible areas near the paved road. We assume that the road has a positive influence for settlements up to 5 km.

Vegetation provides most of the products needed for livestock activities. We classified the vegetation in different classes according to the dominant species and the general products that they provide: woodlands, shrublands, chañarales (*Geoffroea decorticans* small woodlands), and old river bed and flood-plains vegetation. Woodlands are given the highest probability, because they offer wood for fuel, construction, forage, and *P. flexuosa* pods for animal food.

Finally, during the construction period of a new settlement, a "mother" settlement provides water, tools, and labor for construction, until a well is functional (Torres, 2008), so we assumed that the aptitude of a pixel decreases with increasing distances from existing settlements.

For this area, we assume that the economy is relatively less dependent on markets that in other areas, because of the subsistence and extensive characteristics of the region. Trade is generally informal, and people use their animals for family subsistence. There is not a regular and formal commercialization of the products, or refrigeration plants, so we assume, based on experience on the area, lack of official records, and testimonies of the local inhabitants, that people sell their animals informally, upon demand from local consumers or visitors to the area. There are no other paved roads in the area, and the dirt roads need to be accessed in 4 × 4 vehicles.

Although there is some dynamics in settlement and abandonment, there are no data to monitor or validate that information. Testimonies of local settlers indicate that some settlements are abandoned because of poor water quality, for example. These settlements are occasionally resettled for demographic pressures, and subsequently abandoned (testimonies of people from "El Diamante"). In the model, we aim to simulate the final settlement distribution, so low quality places will have a lower probability of being settled. This simplifying approach approximates what happens in the real world, because these places are settled and abandoned, resulting in unsettled environments most of the time.

### 2.2.1. Input grids

In order to simulate the area of interest (Fig. 1), a square area was divided in 22,500(150 × 150) square pixels of 56.25 ha (750 m × 750 m) each, which we consider an appropriate resolution to represent the settlement processes modeled. Seven input grids were elaborated for the region using different maps(Fig. 2).

(a) Initial settlements. The layer of initial settlements to start the simulations was made using a map of settlements from 1928 (IGM, 1928), which was digitalized and transformed to a 750 m pixel raster.

(b) Paved road 142. This layer was digitalized from a georeferenced mosaic of TM Landsat images of the study area (path 231 rows 082 and 083 (NASA Landsat program, 2001, 2002)), and transformed to 750 m pixel raster map. The resulting road map has a wider road than in the real terrain, because pixel sides are 750 m. The road 142 was built in 1975, so we include the input road layer at the corresponding time step.

(c) River layer. The San Juan, Desaguadero and Mendoza Rivers were digitalized from a georeferenced mosaic of TM Landsat images of the study area (path 231 rows 082 and 083 (NASA Landsat program, 2001, 2002)), and transformed to a 750 m pixel map.

(d) Initial Vegetation layer. We made a map of the presumable vegetation of the area one hundred years ago, based on the potential distribution of *P. flexuosa* woodlands (Villagra et al., 2010), combined with current vegetation maps. We made the current vegetation map with a non supervised classification from a georeferenced Landsat 5 TM mosaic (path 231, rows 082 and 083) acquired in March 8th 2011. Current vegetation was initially classified in 15 classes by spectral signature similarity. Then these classes were regrouped in 5 vegetation classes: Woodland, shrubland with high vegetation cover, shrubland with low vegetation cover, Chañarales (*Geoffroea decorticans*) and old river bed-floodplain vegetation. This resulting map was corroborated with vegetation field data obtained during April and May 2011, which resulted in a 96% match between the classification and data from 50 survey sites. Then the 30 m pixel image was resampled at 750 m pixel with a nearest neighbor resampling method (ENVI Resize Data Spatial/spectral module; ENVI, 2003), which uses the nearest pixel value as the output pixel value. There is not a historic vegetation map for the region, but the main changes may have occurred by clear cutting for railroad and vineyard construction, and animal foraging around settlements (Alvarez et al., 2006; Goirán et al., 2012). Based on this knowledge, we made a historical map transforming the current degraded areas (low cover shrublands) into high cover shrublands, and redefining woodlands to match the map of potential *P. flexuosa* woodlands elaborated from environmental factors (Villagra et al., 2010). The other vegetation classes, associated with old and present river beds (chañarales and floodplain vegetation) were not changed for the historic map. The resulting historic map has four vegetation classes: Chañarales, woodlands, high cover shrublands, and old river bed-floodplain vegetation, because three of the seven classes result from human degradation.

(e) Water table depth. Values for each pixel were calculated from a digital elevation model and a potentiometric map of the unconfined aquifer. The potentiometric map, which indicates hydraulic heads, or water table heights above sea level, *wh*, was obtained from Gomez et al. (2014). This map was made with a scale of study of 1 well every 150 km$^2$, yielding equipotential lines every 10 m. A value of hydraulic head was assigned to each 750 m pixel with interpolation. The surface elevation above sea level, *z*, was obtained from a digital elevation model (SRTM-DEM, Shuttle Radar Topography Mission -Digital Elevation Model) developed from radar data collected during the year 2000 (USGS United States Geological Survey, 2004), and validated with local geodesic studies (Aranibar et al., 2011). Source for this data were the Global Land Cover Facility [http://www.landcover.org]. Elevation data were resampled to a 750 m pixel map. Water table depths for each pixel, *w*, result from the difference between elevation, *z* and *wh*. This map was classified into 3 groundwater depth classes: less than 15 m (accessed by manual tools), 15–25 m (accessed with simple mechanical tools), more than 25 m (accessed with more complex and expensive, generally government-supported technology). These values are kept constant during the simulation, because low local precipitation does not cause significant recharges and *wh* fluctuations (Jobbágy et al., 2011).

(f) Old river bed. This grid was made from a geomorphological map of the area (Goirán et al., 2012), which differentiates the old river beds from other geomorphological units.

(g) Mask. Pixels that fell outside the area of interest because they do not represent traditional livestock settlements (i.e., irrigated oases, mountains) were removed from the simulations using a mask of zero total probability values for settlements. This resulted in an irregular simulated region of 17,465 pixels, framed by the rivers and an irrigated oasis.

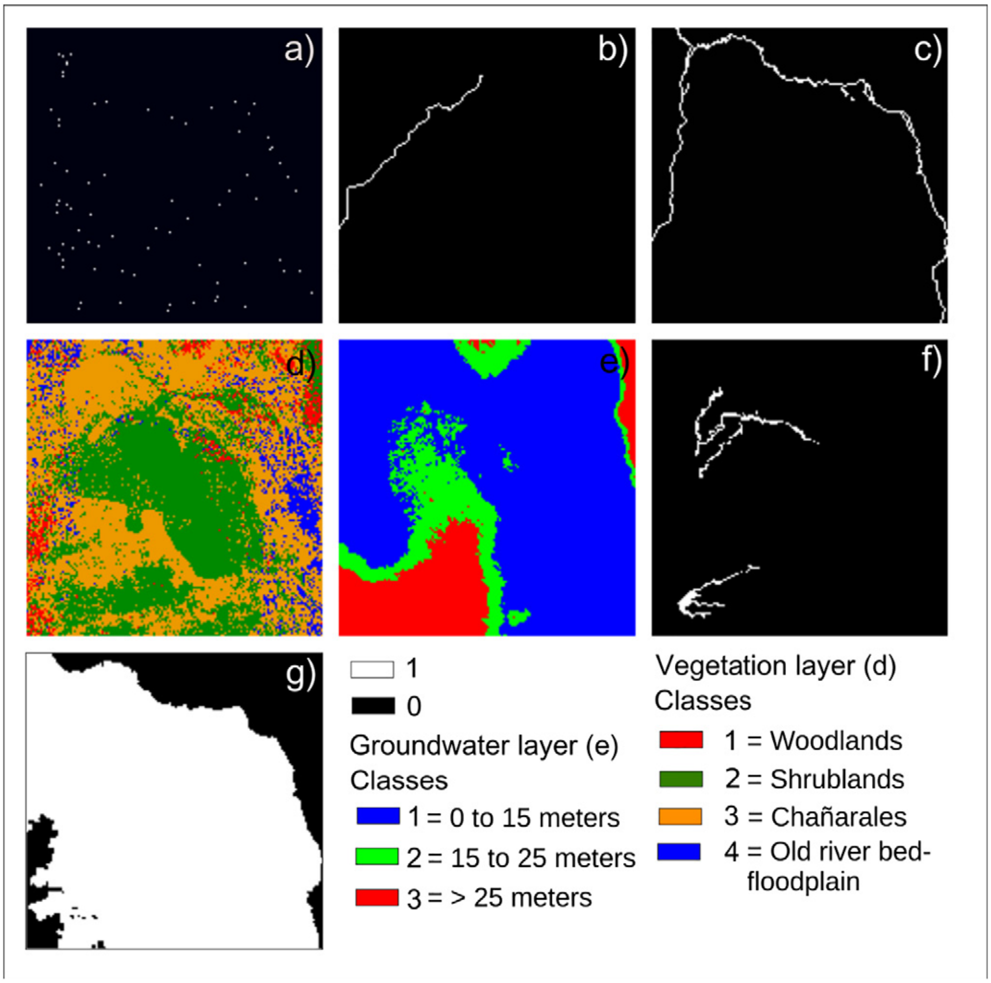

**Fig. 2.** Input grids showing the environmental features represented in layers: a) Initial settlements, b) Paved road 142, c) Rivers, d) Initial vegetation, e) Water table depth, f) Old river beds, g) Mask.

This treatment of boundary conditions is justified in the study area because rivers prevent animal movement and settlement interactions outside the defined area. Furthermore, outside the area, traditional settlements are uncommon because geopolitical or environmental factors, such as land and water rights, mountains, or higher dunes, favor other land uses (i.e., agriculture, unoccupied lands).

### 2.2.2. *Input parameters*

The parameter format used to run the simulations is presented in Millán et al. (2016), and the values for the real case simulation are presented in Table 1 of this paper. The number of steps used was chosen to obtain the final number of settlements that we needed to model, and related to real time a posteriori. A parameter sweep was executed to identify the probability for certain factors that would minimize the residuals between simulations and observations.

Partial probabilities for each environmental factor were calculated from the input grids, assigning probability values according to the following rules:

(a) Distance to Road: In order to represent the decreasing influence of the roads with increasing distances (in km), we categorized these in three possible classes with an associated probability (*Proadmax, Proadmed* and *Proadmin*): (0,3] => *Proadmax* = 1.0; (3, 5] => *Proadmed* = 0.3 (chosen with a parameter sweep); and (5,+∞] => *Proadmin* = 0.1. Because the road N 142 was built in 1975 (Dirección Nacional de Vialidad, personal communication), the road is included in the simulations from time step 940 (47 years after the simulation started).

(b) Distance to River: In order to represent the decreasing influence of the rivers with increasing distances (in km), we categorized these in three possible classes with an associated probability: (0,3] => *Privermax* = 1.0; (3, 5] => *Privermed* = 0.5 (chosen with a parameter sweep); and (5,+∞] => *Privermin* = 0.3 (chosen with a parameter sweep).

(c) Distance between Settlements: The different distance classes between settlements were chosen based on a spatial analysis of the real settlements (Goirán et al., 2012), which showed a high aggregation between 1.5 and 2 km. The distance classes (in km) for this factor are: (0,1.7] with an associated probability of *Psettlmax* = 1.0 and (1.7,+∞] with a probability of *Psettlmin* = 0.1.

(d) Probabilities given by vegetation type, *PVeg*. Initial vegetation was classified into 4 classes: woodlands, high cover shrublands, chañarales, and old river bed-floodplain vegetation. Initial probabilities related to each vegetation type (*PVeg1* to *PVeg5*) were chosen based on the resources offered by each vegetation type, such as forage and wood production, and palatable species. Woodlands, where *PVeg1* = 1.0, are the most valuable class because they provide wood for multiple uses, such as construction material for fences, houses and wells, and animal forage during the entire year, including annual grasses during the summer, perennial shrubs, and *Prosopis* fruits, which are collected and stored for winter reserves (Allegretti et al., 2005). Shrublands provide forage during the entire year, but lower quality and quantity of wood, so the corresponding *Pveg2* value was assumed to be lower than *PVeg1*, and its value was explored using the parameter sweep. Chañarales and old river bed-floodplain vegetation provide a lower amount of forage for livestock, and they cover a low extension of the landscape, so they were assigned $PVeg3 = PVeg4 = 0.3$. *VegRate*, the *PVeg* decreasing rate with time around settlements, reflects gradual vegetation degradation caused by grazing and wood extraction, which represents the decreasing grass, wood, and total vegetation cover observed around settlements (Goirán et al., 2012; Meglioli et al., 2013). This degradation causes a decrease of the probability assigned to each Vegetation type (*PVeg*) with time around settlements, which represents changing vegetation types. At the final time step of the simulation, final *PVeg* values are converted to vegetation types according to the rules defined in Table 2. We include a 5th vegetation type, resulting from the degradation (decreasing *PVeg*) of shrublands into low cover shrublands. Woodlands may be converted into high cover shrublands, and these into low cover, degraded shrublands, according to the reduced *PVeg* at the end of the simulation, as detailed in Table 2. The new vegetation type represents degraded areas near settlements, where total vegetation, grass, and shrub cover is low, as a result of vegetation removal by animals and humans (Meglioli et al., 2013). We presume that low cover shrublands were not present at the initial simulated time, because they are generated by continuous impacts on the environment. Although *PVeg* values in old river bed-flood plain vegetation were allowed to decrease during the simulation, the structure was assumed to remain constant, because this vegetation type is characterized by fast growth species, which grow after occasional flooding, and are not used by local population for wood-forestry products, in contrast to *P. flexuosa* woodlands. In fact, old vegetation maps (Prieto, 1997) describe riparian vegetation in the same places as found today, suggesting that livestock has not significantly changed its structure.

(d) Probabilities assigned to water table depth classes, *Pwatertab*, were chosen considering the effort of manually building a well, and the need of machinery for greater depths. We divided water table depths in 3 classes, and assigned decreasing probabilities with increasing depths, from class 1 (less than 15 m) to class 3 (more than 25 m). The first and third groundwater depth classes were assumed to have the highest and lowest probability, respectively, so $Pwatertab1 = 1.0$ and $Pwatertab3 = 0.1$. The value of the intermediate class, *Pwatertab2*, was assumed to be lower than the first class, because of the greater effort required and risk of collapse in these sandy sediments. The value of *Pwatertab2* was explored with the parameter sweep. We assumed constant water table depths during the simulation in each pixel because of the low extraction rates given by manual pumping, the negligible local recharge rate given by precipitations (Jobbágy et al., 2011), and testimonies of local settlers, who reported constant water table depths during settlements history.

(e) Probabilities associated with old river beds. We assigned two probability classes for old river beds or "paleocanal", for pixels located in and outside old river beds (*Ppaleomax* and *Ppaleomin*). $Ppaleomax = 1.0$ inside old river beds, and *Ppaleomin*, outside old river beds, was explored with the parameter sweep.

The following list details the factor parameters with the format required by the simulation software model. These values are explained in the previously described rules (bullets from *(a)* to *(f)* in the previous paragraph, see Millán et al. (2016) for more information on how to use the factor format):

- factor; road; 1 3 0 3 5 1.0 0.3 0.1
- factor; river; 1 3 0 3 5 1.0 0.5 0.3
- factor; watertab; 2 3 1 2 3 1.0 0.7 0.1
- factor; oldriver; 2 2 1 0 1.0 0.2
- factor; mask; 2 2 0 1 0.0 1.0
- factor; vegetation; 3 5 1 2 3 4 5 1.0 0.9 0.3 0.3 0.3 2 0 2 0.015 0.010
- factor; settle; 4 2 0 1.7 1.0 0.1

The factors are described with the keyword "factor", followed by the name of the factor, an integer number to select the type of factor (1,2, 3 and 4). Finally, the values required by each type of factor. The four types of factors are:

- Type 1: distance-related that consists of ranges of distances with an associated probability for each range. Used to simulate distance to road and rivers.
- Type 2: assigns a probability to an attribute of each pixel in the grid. Used for groundwater, old river beds and a mask.
- Type 3: assigns different probabilities to pixels in the grid according to an input map, and decrements that probability every step of the simulation around settlements. Used for reducing the vegetation around settlements.
- Type 4: used to store the information of the initial settlements in the grid, and to store the newly created settlements during the simulation.

### 2.2.3. Model output

1. Simulated settlement map: the output file of simulated settlements is presented as a 750 m pixel map.

**Table 2**
Criteria used to elaborate the output vegetation map at the end of the simulations. The input vegetation maps have only four vegetation classes. The establishment of a new settlement decreases *PVeg* with time in neighbor pixels according to *VegRate*. The final vegetation map is elaborated with the initial vegetation class and the resulting *PVeg* at the end of the simulation, reassigning vegetation classes as described below.

| Initial vegetation class | PVeg at the end of the simulation, resulting by vegetation degradation | Vegetation class at the end of the simulation |
|---|---|---|
| 1 (Woodland) | 0.7 to 1 | 1 (Woodland) |
| 1 (Woodland) | < 0.7 | 2 (High cover shrubland) |
| 2 (High cover shrubland) | 0.7 to 1 | 2 (High cover shrubland) |
| 2 (high cover shrubland) | < 0.7 | 3 (Low cover shrubland) |
| 4 (Chañaral) | All | 4 (Chañaral) |
| 5 (Old river beds vegetation) | All | 5 (Old river bed vegetation) |

2. Vegetation map: we built a vegetation map that represented the degraded vegetation at the end of the simulations using the final partial probabilities given by vegetation type (*PVeg*) across the grid. These values resulted from the gradual modification of *PVeg* around new settlements, during the course of the simulations. We re-assigned a vegetation class to each range of probability values, attempting to represent the types of vegetation that result from degradation associated with settlement activities (grazing, wood, and firewood extraction). The resulting vegetation map depends on the original vegetation (input grids) and the decreasing partial probabilities on each pixel near established settlements.
3. Histograms: we plotted pair correlation histograms of simulated settlements (settlement-settlement with pair correlation function, $g(r)$, settlement-road, and settlement-river distances) (explained in Millán et al. (2016)), averaging the results of the N simulations. We then calculated the residuals for each histogram between a simulated (average of N simulations) and a reference case with the formula:

   $$\sum_{i=1}^{n} (H'_i - H_i)^2 \tag{1}$$

   where $H'_i$ is the value of histogram $< H' >$ at bin $i$ for the simulated distribution, and $H_i$ is the value of histogram $< H >$ at bin $i$ for the reference case.

   We used this approach for two objectives: to check the stability of the model, and to compare it with the real distribution of settlements. For the first objective, the reference case is the average of N-1 simulations as in Millán et al. (2016), and for the second objective, the reference case is the histogram of the spatial distribution of real settlements in the study region. We analyzed the stability of the model including all parameters and input files of the study area, running increasing number of simulations, and calculating the residuals averaged at increasing number of simulations. We chose intermediate parameter values for intermediate distance classes, as detailed in Fig. 3. These simulations indicate that steady values are reached for settlement-settlement and settlement-road histograms with approximately 20 to 30 simulations. For settlement-river distances, residuals have small fluctuations with approximately 50 simulations (Fig. 3).

   To compare simulations with observations, and identify important factors for settlement dynamics, a map of real settlement distribution was obtained from Goirán et al. (2012), which was made with existing records from local government offices (Secretaría de Medio Ambiente Mendoza, 2001a, 2001b), and complemented with settlements detected with Google Earth (Google, Mountain View, CA, USA, http://earth.google.es) images, considering the presence of corrals or housing structures, in addition to a clear area around them, as evidence of active livestock settlements. The map from Goirán et al. (2012) was re-sampled to 750 m pixels, to compare it with model results. Because people do not depend on government assistance to build wells and settlements, there are no complete and updated records of livestock settlements and their condition (whether they are active or abandoned), so we assumed that all settlements detected with the images were active.

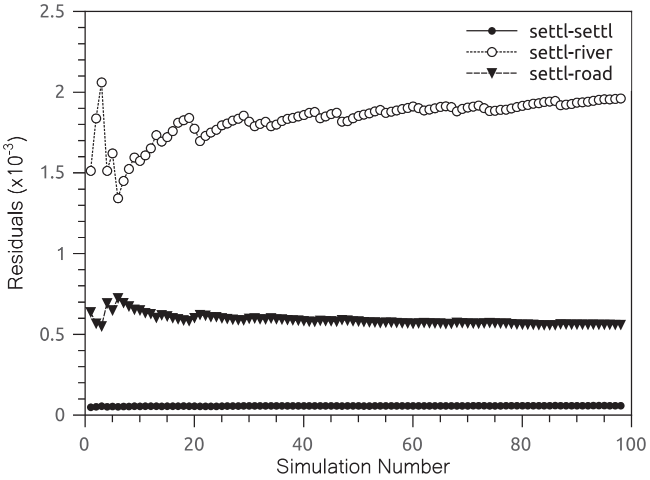

**Fig. 3.** Average residuals vs number of simulations, with $Pset = 0.14$, $Ppaleomin = Privermed = Proadmed = PVeg2 = Pwatertab2 = 0.5$, $Privermin = 0.1$.

#### 2.2.4. Analysis of the relative importance of environmental factors with a parameter sweep

Based on the results of model stability (Fig. 3 and Millán et al. (2016)), and the computational requirements to run multiple simulations, we run 30 simulations with each combination of parameter values for the following parameters: *Privermed, Privermin, Proadmed, Ppaleomin, PVeg2, Pwatertab2* and *Pset*. We assigned a maximum probability value to optimum conditions ($Privermax = Proadmax = Pwatertab1 = PVeg1 = Ppaleomax = Psettlmax = 1$). Probabilities ranged from 0.1 to 0.9, with a step of 0.1, restricting parameter combinations to those that represented decreasing probabilities with increasing distances from rivers, roads, and surface soil: $Privermed > Privermin$; $Proadmed > Proadmin = 0.1$; $Pwatertab2 > Pwatertab3 = 0.1$.

The parameter combinations described above were run with 3 values of *Pset*: 0.12; 0.14; and 0.16, resulting in 373,248 combinations. We created a Ruby script to run the cases needed for the sweep, combining all the possibilities for the parameters listed above. Using a mini-cluster of three computers (AMD FX-8350 with eight cores running at 4.0 GHz), it took ~12 days to run the sweep. Since there are a total of 373,248 parameter sets, and for each N = 30 simulations are needed, there are a total of ~11.2 million simulations required. Perfect parallel efficiency using the timing for a single case (1.7 s) would give ~9.1 days. The excess execution time means that, as expected, parallel efficiency is not perfect but fairly good

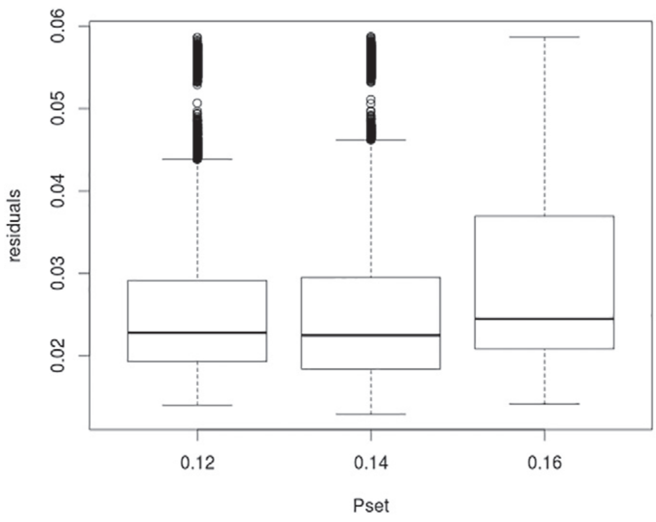

**Fig. 4.** Residuals of the simulations resulted from the parameter sweep with different *Pset* values. Only parameter combinations that yielded an average number of settlements with $400 < Nsettlements < 550$, $Nstd < 80$ are plotted.

given the extra time needed for memory and disk access when running in parallel. Based on this sweep we have been able to select nearly optimal values for those seven variables, reducing the error for the correlation pair for the road and river. This parameter sweep can be improved by using a GPGPU implementation of the settlements dynamics code already presented in Millán et al. (2016). The number of simulations executed in the parameter sweep could also be reduced by using Genetic Algorithms (Whitley, 1994) or the Data Assimilation technique (Houtekamer, 1998).

We calculated the residuals between the simulations and the real case for each pair correlation function (settlement-settlement, settlement-river, and settlement-road) for each set of input parameters.

Using the results of this sweep, we restricted the simulations that yielded an average number of settlements between 400 and 550 (similar to the real number of settlements), with a standard deviation lower than 80. We used this subset of simulations to explore parameter values that reduced the residuals between simulations and observations, plotting parameter values versus residuals, and sequentially excluding values that resulted in maximum residuals.

We then run 100 simulations with parameter values that yielded minimum residuals, and additional sets of 100 simulations sequentially removing each single factor, to analyze the impact of different factors on the histograms and residuals.

## 3. Results

Using the plots of residuals and *Pset* values of the parameter sweep, we first excluded simulations with *Pset* = 0.16, because the resulting residuals were higher than those with the *Pset* = 0.12 and 0.14 (Fig. 4). The plots of the other 6 parameters analyzed, with the subset of *Pset* = 0.14 and 0.12, indicate clear variations of residuals with variations of the three parameters related with surface water availability, *Privermed, Privermin*, and *Ppaleomin* (Fig. 5). The other parameters, *PVeg2, Proadmed*, and *Pwatertab2* did not cause a marked variability on the residuals (Fig. 5). From this analysis, the following parameter values, which yielded lower residuals, were selected: *Privermed* = 0.5; *Privermin* = 0.3; *Ppaleomin* = 0.2. Although minimum residuals were obtained with *Privermin* = 0.4, there was not a combination of this value with *Privermed* = 0.5 and *Ppaleomin* = 0.2 that satisfied the restrictions of mean and standard deviation of number of settlements, so *Privermin* = 0.3 was selected. With this subset of parameter values, *Pset* = 0.14 (Fig. 6), *PVeg2* = 0.9, *Pwatertab2* = 0.7, and *Proadmed* = 0.3 resulted in the minimum residuals.

Running 100 simulations with the parameters selected with the sweep, and mentioned above, the exclusion of the single factor that most increased the residuals was the old river bed, *Ppaleomin*, with a six fold increase, being followed by distance from rivers, with a three fold increase (Figs. 7 and 8). Removing the effect of the road, had a slight increase in the residuals, while removing groundwater depth (*Pwatertab*) and vegetation (*PVeg*) did not change the residuals.

The regional pattern of simulated settlements with the optimized parameters matches the real settlement distribution, with high densities in the lacustrine plains and near rivers, and more sparse, but not uniform, settlements in the aeolian plain, far from rivers (Fig. 9).

The optimized simulations resulted in an average of 167 settlements (44%) established randomly, mainly in areas of the aeolian plain distant (more than 7.5 km) from rivers, and 213 by maximum

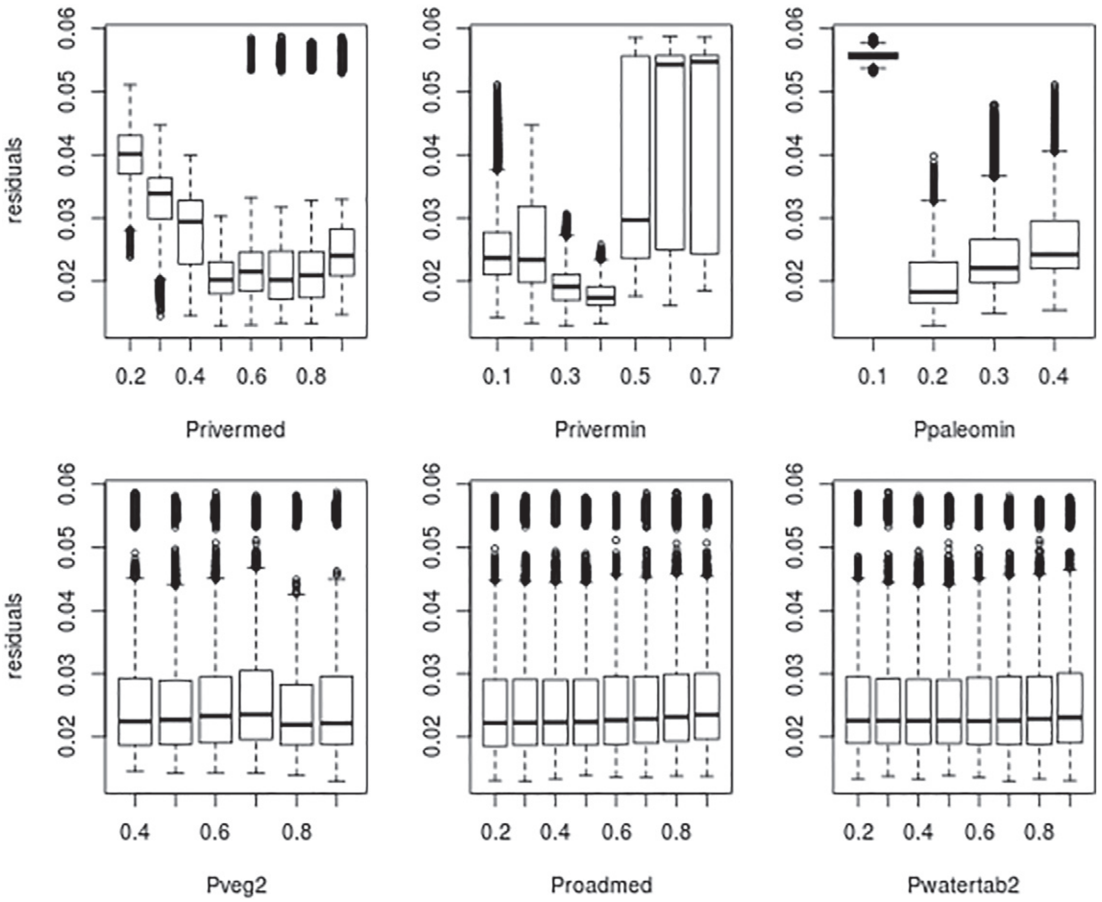

**Fig. 5.** Residuals of the parameter sweep with different values of *Privermed, Privermin, Ppaleomin, PVeg2, Proadmed*, and *Pwatertab2*. Only combinations with 400 < *Nsettlements* < 550, *Nstd* < 80, *Pset* = 0.12, and *Pset* = 0.14 are included.

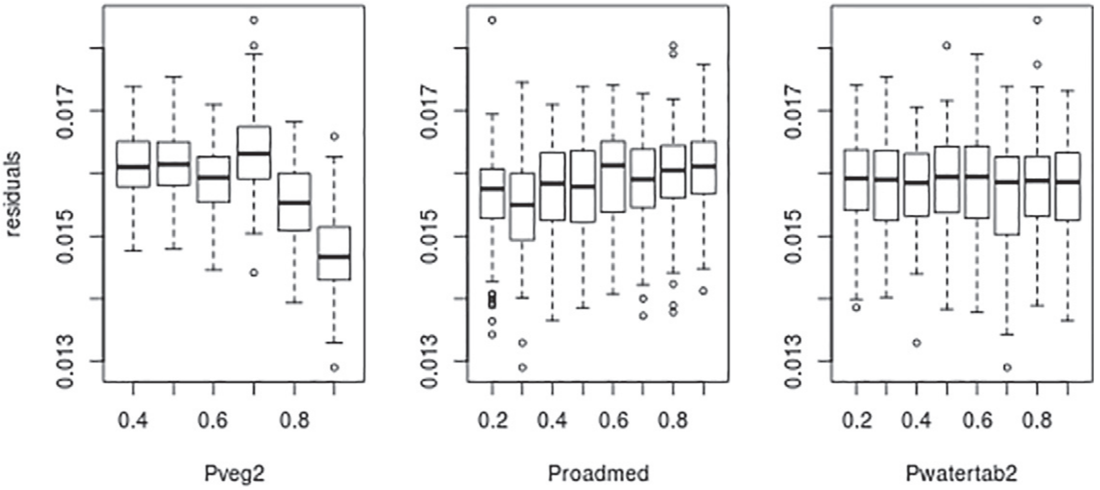

**Fig. 6.** Residuals of the parameter sweep with different values of *PVeg2*, *Proadmed*, and *Pwatertab2*. Parameter combinations with the restrictions of Figs. 4 and 5 ($400 < Nsettlements < 550, Nstd < 80$, $Pset = 0.12$, and $Pset = 0.14$), and optimized parameters values for $Privermed = 0.5$, $Privermin = 0.3$, and $Ppaleomin = 0.2$, are included in this plot.

probability, mainly near rivers. The histograms for settlement-settlement distances near (up to 10 pixels or 7.5 km) and far (more than 10 pixels or 7.5 km) from rivers show different spatial distributions, with a lower aggregation in the later case (Fig. 10). The high aggregation of real settlements in the first histogram bin in Fig. 10b is given by a cluster of settlements in the NE of the region, more than 7.5 km away from the river. Excluding this cluster, most settlements in the aeolian plain show a low aggregation, and random distribution (Fig. 9). The resulting vegetation map, which includes the degradation given by livestock settlements, shows a similar distribution of vegetation classes as in a real vegetation map, although the reduction of vegetation around settlements, and the total remaining area of woodlands are higher in the model than in the real case (Fig. 11). In Fig. 12 there are two grid maps with the probability of each cell for the first and last simulated steps. In the first step, total probabilities do not include the partial probability of roads (which is added at step 940) or the decrease on partial probability due to vegetation loss. Total probabilities in the last step include all factors, and shows a reduction in probability values around settlements caused by gradual decrease of vegetation (VegRate).

## 4. Discussion

The hypothesis, that surface and groundwater are the most important determinants of livestock settlement spatial distribution, was partially supported by our simulations, which indicated a clear effect of surface water (rivers and old river bed parameters), but a negligible effect of groundwater depth on settlement spatial distribution. The study by Goirán et al. (2012) indicated areas of settlement aggregation, but the relative importance of groundwater, rivers, old river beds and roads could not be distinguished, because they overlap in several areas. The simulations of settlement dynamics presented in this study provide an evaluation of different environmental drivers of settlements. Parameters related to surface water (rivers and old river bed) were the most important drivers to approximate the real settlement spatial distribution. The residuals reached minimum values only when the probability of the third distance class from rivers (*Privermin*) was less than half the probability of the first distance class (Fig. 5). The probabilities associated with the old river bed also needed to be lower outside the old river bed (*Ppaleomin*) in order to reach minimum residuals. The residuals increased six and three times if the old river bed or river probabilities were removed from the optimized simulations, respectively (Fig. 8). Several services are better in the old river bed, such as higher surface water availability than in the aeolian plain, better groundwater quality, and easy access, given by smooth slopes. However, it is possible that present day occupation is affected by a memory of past environmental conditions, although present and past effects are difficult to distinguish. Archaeological studies show most of pre-hispanic occupancy near rivers and lakes, both in the Mendoza and Tunuyán rivers (Cahiza and Ots, 2005; Llorca and Cahiza, 2007). Pre-hispanic remains (i.e. fish bones) indicate permanent occupancy and surface water in the main old river bed (Cahiza and Ots, 2005; Chiavazza and Olavaria, 2004; Llorca and Cahiza, 2007). Settlements may persist in the same locations as in the past, although present day conditions have changed. Guanacache wetlands, which have been populated since pre-hispanic times (Abraham and Prieto, 1991), have almost dried at present as a consequence of geologic and water use changes. However, settlement aggregation persists in these areas to the present. Rivers have lower flows at present, because of upstream use in irrigated oases, and the lakes that they sustained are no longer permanent, because of deep channeling and lower flows (Sosa, 2012). Some settlements are clustered in the river plain, at more than 7 km from the present river channel (Fig. 9) (outside the area of river influence in the present, simulated with the model). These settlements have probably been influenced by the past river channel, which has shifted slightly to the East. The old river bed has been dry since 1778 (Prieto, 1997), but a high aggregation remains in this area, probably because there are no better conditions in the rest of the region to sustain the increasing population. Multimodel studies suggest that in vulnerable regions, climate change will significantly add to the problem of water scarcity that is already arising from population growth, causing domestic instability and migration (Schiermeier, 2013). In our study area, decreasing water availability associated with decreasing river flows is not reflected in changes of occupation patterns. However, decreased water availability probably affects productivity, human-ecosystem interactions, and life quality, so it would be important to plan future development as a function of present and future resource availability.

The construction of the paved road along the old river bed for most of its length was also followed by the provision of electricity and other goods. However, the apparent benefits of the road on

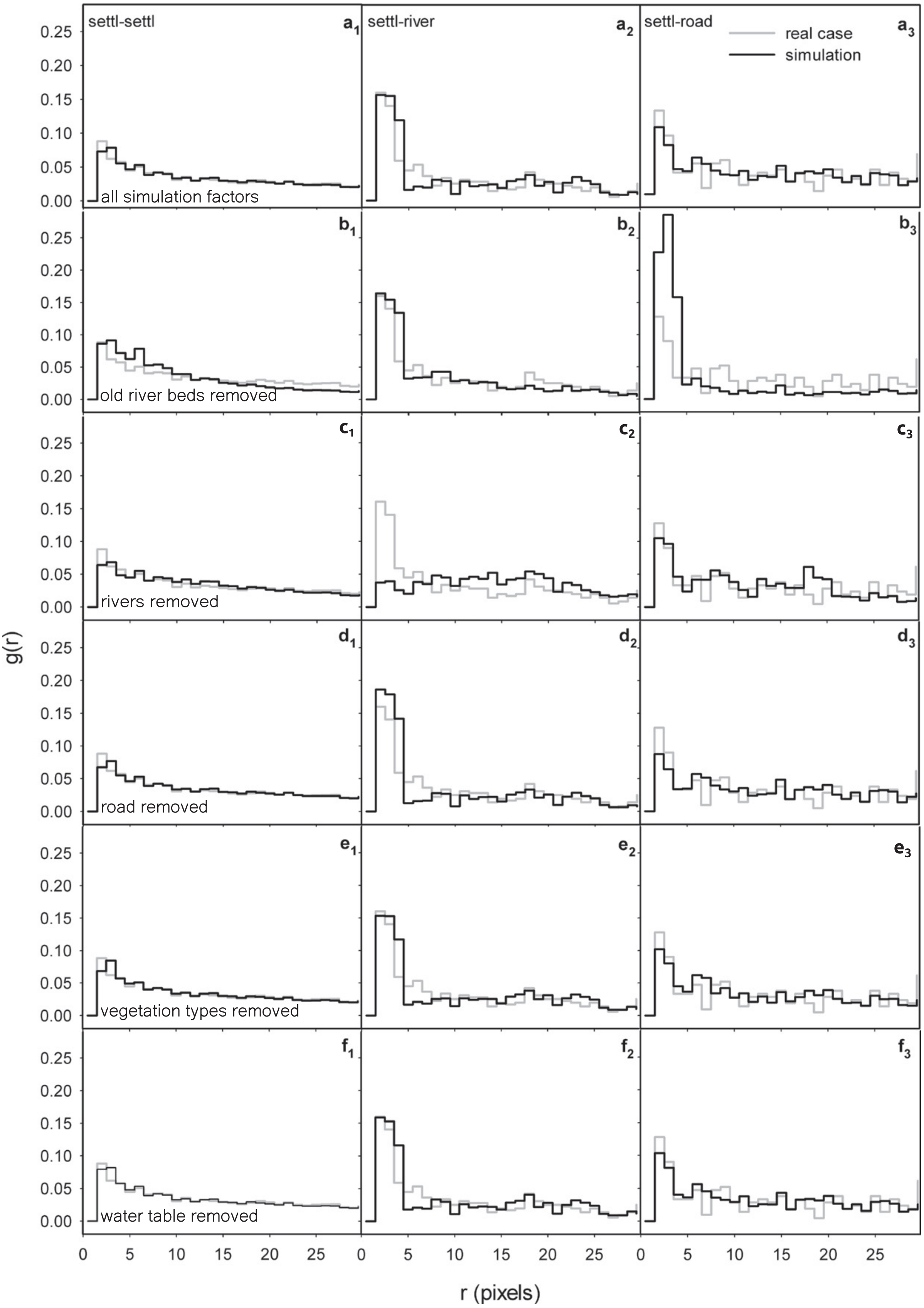

**Fig. 7.** Pair correlation histograms for distance between settlements (1-settl-settl), settlement to river (2-settl-river), and settlement to road (3-settl-road ), with the optimized parameters; (a) Simulations with all factors; (b) without old river beds; (c) without river; (d) without road; (e) without vegetation types; (f) without water table simulation. r (pixels) is the distance in pixels, where one pixel=0.5km.

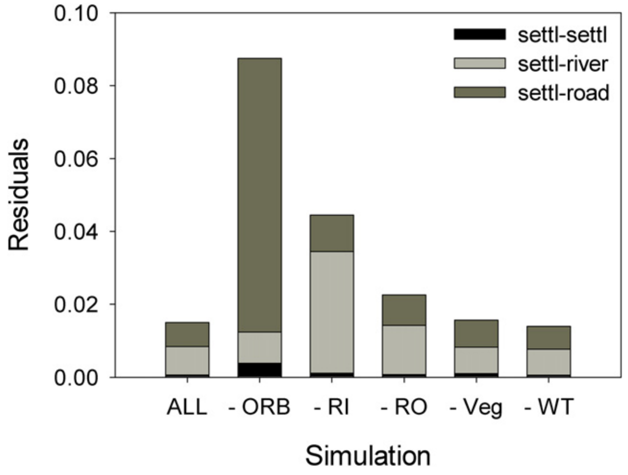

**Fig. 8.** Total residuals, averaged after 100 simulations, for the cases presented in Fig. 7. (ALL) Simulations with all factors; (ORB) without old river beds; (RI) without river; (RO) without road; (Veg) without vegetation types; (WT) without water table simulation.

settlements are not strong enough to cause a significant attraction or aggregation. This suggests that past and present benefits of the old river bed associated with water availability have a higher impact on settlement establishment than technological and transport benefits given by the road. This is supported by observations of new settlements that were established along the recently built aqueduct, after the input maps for these simulations were elaborated. Water availability is clearly more important to settlers than electricity and transportation.

A finding that did not agree with our hypothesis is the insignificant role of groundwater depth on settlement establishment. Most of the region has groundwater depths that may be accessed by manual metal tools (up to 15 m in interdune valleys). Settlers do not have detailed information about water table depths, so probably they do not include it in their decisions to establish a settlement. Once settlers start to excavate a new well, they may continue drilling even if the water table is a few meters deeper than expected. If other factors are favorable for livestock activity, people may invest the necessary effort to reach deeper groundwater, in spite of the difficulty.

Vegetation does not appear to influence settlements spatial patterns, contrary to our hypothesis. Vegetation resources from different vegetation types are probably transported to other areas for construction and fuel, during construction and maintenance periods, while water is needed everyday to keep the animals. People may prioritize water over vegetation "on site" availability, and invest the necessary efforts to transport vegetation goods. As for animal food, goats, the main animals raised in the area, consume shrubs and grasses present in both, forests and shrublands. *Prosopis* pods, offered only by woodlands, are collected by the owners and stored for winter reserves, so this food resource may also be transported to the settlements from the surrounding vegetation. The simulated vegetation map resulting from the degradation of the vegetation around settlements has a similar spatial distribution of different vegetation classes as the remotely sensed (real case) vegetation. Yellow areas in Fig. 11, representing low cover shrublands, appear in simulations and remotely sensed data in the North West and North East of the grid. Patches of orange areas (high cover shrublands) are immersed in the area of historic woodlands (green areas), in both, simulations and observation. However, the areas of extreme classes, such as low cover shrublands (degraded areas) and woodlands (well conserved woodlands) are higher in the simulated map than in the real case. Degradation around settlements seems to be overestimated in the simulations. The lower cover of woodlands in the real than in the simulated map may be given by forest clear cutting during the end of the XIX and beginning of the XX centuries, for railroad and vineyard construction, which was not simulated in the model (Rojas et al., 2009). Another source of error on the simulated vegetation is the initial vegetation map, elaborated from the potential distribution of *Prosopis flexuosa* woodlands (Villagra et al., 2010), which is strongly dependent on the environmental factors found on the remaining woodlands.

We also hypothesized that new settlements have to be located near a mother settlement, which is simulated in the model as decreasing probabilities with increasing distances from existing settlements. Our results, which show lower residuals for settlement-settlement distances than for settlement-road and settlement-river distances, support this hypothesis. However, the simulations locate settlements at larger distances than in real cases, as observed in the first and second histogram bins (Fig. 7a). This may be due to the overestimation of land degradation by the model, which decreases probabilities around settlements, acting as a "repelling" force. The over-representation of degradation may be given by the lack of vegetation processes simulated in the model, such as vegetation resilience, interactions between landscape units, and among species. Studies done in the region indicate that vegetation has a high resilience, recovering vegetation cover during periods of

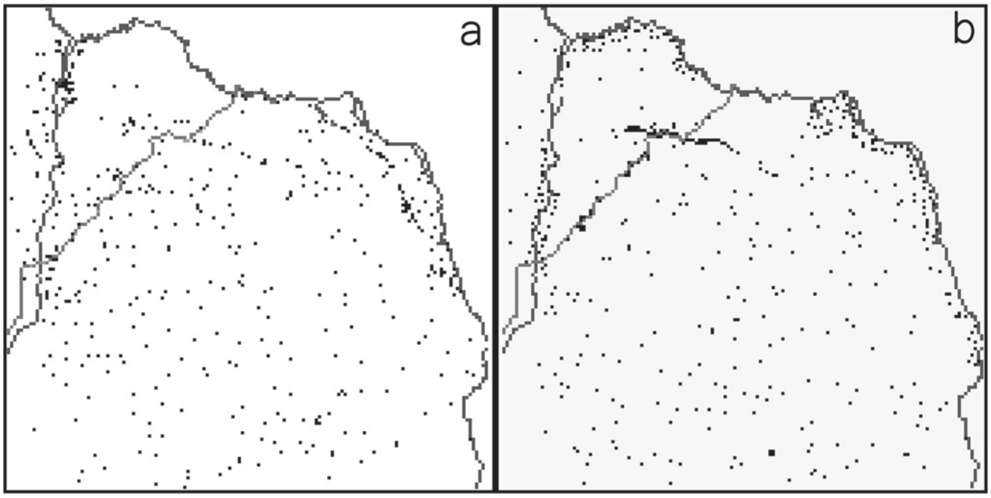

**Fig. 9.** a) Real settlements distribution and b) Simulated settlement distribution using parameters optimized with the parameter sweep. One representative instance of the N=100 simulations was chosen for this figure.

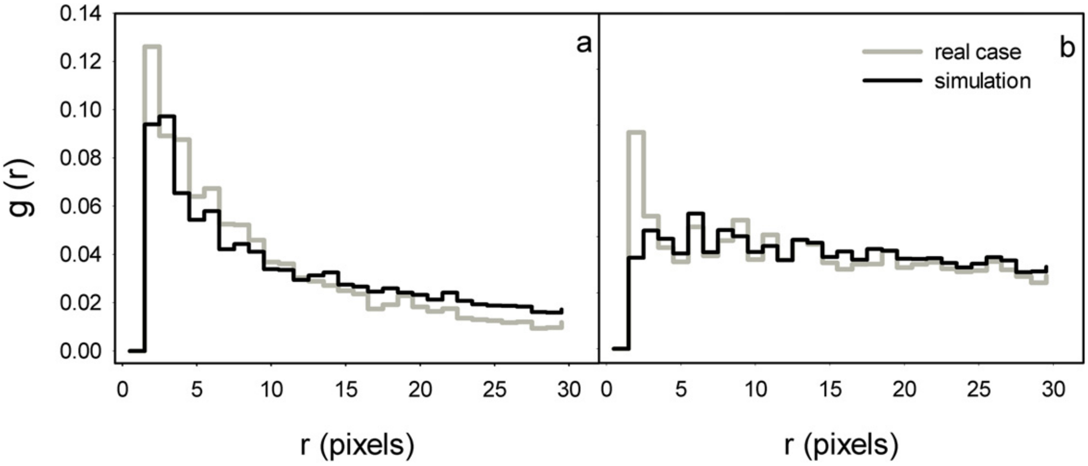

**Fig. 10.** Pair correlation histograms of settlement-settlement distances for areas near (a) and far (b) from rivers, lakes and old river bed, with the optimized parameters.

abundant precipitations. However, resilience is decreasing in some areas, probably because of continuous effects of livestock (Goirán, 2017). In terms of species interactions, large *Prosopis flexuosa* trees are not cut in the settlements, because they provide shade, food and wood. These trees, remaining in areas of high livestock densities, provide shelter for other species, facilitating their survival in areas with low livestock densities (Cesca et al., 2012), and probably providing resilience to the ecosystem. Although there is evidence to support the occurrence of facilitation and resilience, these processes are not still mechanistically described as to simulate them in a model.

The model simulates reasonably well the different settlement densities at a regional scale, with higher densities and more aggregation near rivers and old river beds, as observed in the real case, and sparser settlements, with a random distribution, in areas of the aeolian plane without access to surface water (Fig. 9). In these areas of the aeolian plane (7.5 km from rivers), all the simulated settlements were assigned at random, because total probabilities were lower than the threshold value, *Pset*, indicating a low aptitude of the area (Fig. 10b). The need to assign settlements at random may indicate past pressures to settle in unfavorable places, such as socio-political drivers that displaced Huarpe individuals to inaccessible sites in the past, seeking refuge from colonial authorities who relocated them to urban and agricultural areas, or Chilean mines as laborers (Escolar, 2007). At present, settlements in the aeolian plain may reflect demographic pressures. Some of these settlements are subsequently abandoned, reoccupied, and reabandoned because of low water quality or isolation (Family of Puesto El Diamante, personal communication).

Historically, Huarpe populations inhabited the whole territory of North Mendoza and South San Juan, but the aeolian plain was not permanently occupied during pre-hispanic times (Chiavazza and Olavaria, 2004). The most productive lands of these provinces were transformed into irrigated oases, and developed for industry and agriculture during the XIX century and to the present. Huarpe individuals and communities may have remained and established in NE Mendoza because the low productivity and difficult access to the lands prevented the expansion of irrigation, agriculture, and urbanization. Social and political factors have been proposed to affect settlements patterns of occupancy, such as family ties (Torres, 2008) and attempts by colonial government to aggregate aboriginals in towns in the lacustrine plains (Prieto, 1997). We did not attempt to simulate settlement family relationships, but the relative importance of social, political, and environmental factors could be analyzed by comparing our results with those from agent based models (Kohler et al., 2012; Macal and North, 2010). Currently, Huarpe descendants inhabit the area and national laws grant them land

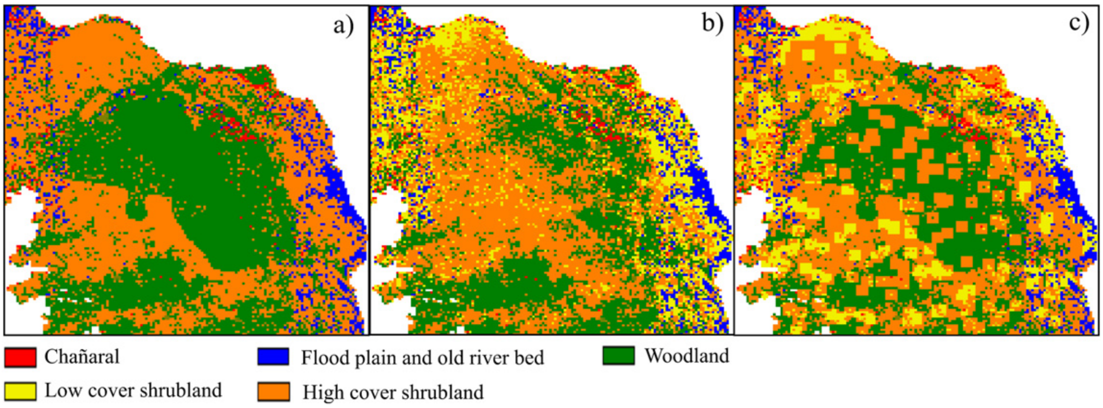

**Fig. 11.** Vegetation maps for the study area. (a) Initial (input) vegetation one hundred years ago obtained from potential and historic distribution of the vegetation, (b) real present-day vegetation according to a non-supervised classification from Landsat TM and (c) final simulated vegetation including the effect of degradation around simulated settlements, from the same simulation shown in Fig. 9. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

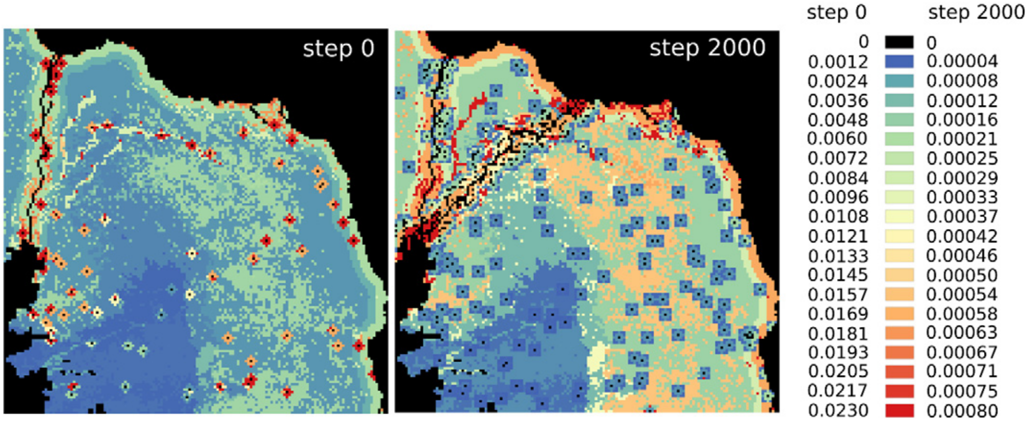

**Fig. 12.** Probability map for the simulated area in the step 0 and the last simulated step (2000), showing a change on the distribution of relatively higher probability areas. Areas of higher probabilities are almost exclusively located near river beds and rivers in step 0. In step 2000, high probability areas are affected by subsequent settlements, with repelling and attracting forces, depending on the distance to new settlements, which can produce a reduction of 0.1 in probability for repelling forces. The addition of the paved road in the step 940 also reduces the probability for long distances to 0.1.

property rights (Gobierno de la República Argentina, 1989; Gobierno de la Provincia de Mendoza, 2001). Government efforts also tend to support local inhabitants with the construction of an aqueduct and roads to improve access and communication to the area, financial support for tourism projects, and feed subsidies for livestock owners during drought periods (Municipalidad de Lavalle, personal communication). These political changes and a growing population may increase settlement densities, change their spatial distribution, and increase land use pressure, with unknown effects on natural resources. In addition, possible climate changes and increasing water demand in upstream irrigated oases may decrease even further river flows to the region, jeopardizing all efforts to reach a sustainable development of the area.

Our model suggests that past and present surface water availability are the main positive driver for the livestock sector in the region, overruling other apparently positive factors, such as roads, with the consequent electricity and communication, vegetation, and groundwater depths. Our model could be used to evaluate the effect of changes on environmental factors, such as water provision by aqueducts, road constructions, and deforestation, on settlement dispersion and vegetation degradation in this and other harsh environments, where forest conservation efforts, water scarcity, and human activities overlap.

## 5. Future directions

In order to use this model as a management tool for arid areas, it would be valuable to apply and test it in similar areas, such as the dunes in the north of our study region (San Juan province, Argentina), the Kalahari or Arabian deserts, which are also used by pastoralists. The model can also be tested observing land use changes in the region, such as settlement establishments associated with a recently built aqueduct. Several new settlements not included in the simulations have been established in a well-conserved woodland near the paved road and near a recently built aqueduct. It is clear that water availability encourages settlements, as it has occurred since prehispanic times, so the provision of fresh water would likely change settlement distributions and densities. The effect of new infrastructure or land use decisions, such as roads construction, deforestation, and water provision could be analyzed with the model, by adding these new features in a grid, and observing the resulting settlement distribution and vegetation degradation. Moreover, the recent construction of an aqueduct, after the elaboration of this model, has already caused changes in settlement distributions, similar to those predicted by our model. The families of at least 6 settlements previously located in the aeolian plain moved to areas near the road after the aqueduct was constructed, abandoning their livestock settlements and changing their lifestyle. El Cavadito and La Majada, which used to function as settlements, with a school and health post each, now sustain neighborhoods with tens of houses with people who used to live in the aeolian plain. At least two families from the aeolian plain requested permission to local authorities to reestablish their livestock settlements near the road and aqueduct, and one of them already moved (Telteca park rangers and local inhabitants personal communication). Our study magnified the effect of settlements on vegetation degradation, although it matched the general spatial pattern of vegetation change. Future studies should also include the consequences of different management practices aimed at achieving sustainable use of the environment. This could be achieved with more detailed vegetation monitoring and ecosystem studies, to constrain the vegetation simulation in the model.

The simulation code presented in Millán et al. (2016) and the parameter sweep can be improved using Genetic Algorithms (Whitley, 1994) to reduce the amount of simulations that have to be executed in order to find values that produce low residues.

## 6. Conclusions

The model simulated similar regional patterns of settlement distribution as observed on the land currently, probably because the simple model of surface water limitation, in addition to stochastic effects, still holds, in spite of other driver factors. However, 44% of the settlements were established at random, suggesting the existence of other drivers, which could be related to demographic or socio-political pressures. Our simulations suggest that environmental features related to water availability have a strong effect on settlement spatial distribution in our study area. Settlements also affect vegetation, decreasing vegetation cover around livestock settlements. Rivers and the old river bed are the most important factor that explain settlement distribution. Even though the presence of a road, built along the main old river bed for most of its length, provides many additional services to the rural population (i.e., electricity, drinking water, transport to commercial centers), the old river bed seems more important for settlement dynamics. Groundwater depth and vegetation, however, were not found to be important drivers of settlement, contrary to initial expectations, probably because the entire region has accessible groundwater and forage, and certain vegetation products are transported to the settlements from surrounding areas.

Our results imply that increasing water availability and water quality will modify settlement distribution and pressures on the environment. Future water provision, which is crucial for the development of the rural population, should consider the possible effects of increasing settlement densities around water sources and the pressures on the surrounding environment, to ensure long-term sustainability.

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