Supplementary Material

Where should livestock graze? Integrated modeling and optimization to guide grazing management in the Cañete basin, Peru

The Supplementary Material comprises additional information on the hydrologic models (Section A) and on the rangeland production model (Section B).

A. Hydrologic models

A1. Baseflow model

We used the InVEST seasonal water yield model (v3.3.1) (Sharp et al., 2019). Inputs are rasters of monthly precipitation and evapotranspiration, land use land cover type and hydrologic properties (e.g. curve number), and soil type (Table A1). The model computes the water balance on each pixel: water supply is through precipitation and subsurface flow from upgradient pixels, and losses are through surface runoff, evapotranspiration, and subsurface flow to downgradient pixels. A routing parameter, β, can be used to characterize the subsurface hydrology, i.e. to define the percentage of upslope subsidy available to a given pixel for evapotranspiration. In this application, we set β to 0 to force the model to compute a simple water balance on each pixel, which simplifies the interpretation.

Model estimates for baseflow ranged from 0 to 855 mm in the Reserve, as illustrated in Figure A1. We compared these values with those of a calibrated model of the basin (SWAT, Francesconi, Uribe, Valencia, & Quintero, 2018), where we calculated as the sum of the annual lateral flow and groundwater flow variables. The spatial distribution of baseflow values was consistent between the two models, with a correlation coefficient r^2 value of 0.68 between the SWAT and InVEST baseflow estimates at the subwatershed level. This provides confidence in the capacity of the model to capture spatial differences in baseflow over the entire Cañete basin. However, the SWAT baseflow estimates reached higher values (up to 1587mm). This discrepancy can be explained by the simplification of the water balance in InVEST model (ignoring evapotranspiration of upgradient water for each pixel), as well as the differences in conceptual models (baseflow in SWAT was calculated as the sum of lateral flow and groundwater flow).

Table A1: InVEST seasonal water yield model sources and values (InVEST version 3.3.1)

Name	Source
Monthly precipitation	National Meteorology and Hydrology Service of Peru (SENAMHI), as described by Francesconi et al. (2018). Interpolated (inverse distance weighted)
Monthly ref. evapotranspiration	WorldClim (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005)
DEM	CGIAR-CSI SRTM (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1)
LULC	Peru National Geographic Institute (IGN)
Soil group	Peru National Office of Natural Resource Evaluation (ONERN)
Biophysical table*	CN values from Uribe et al. (Uribe, Quintero, & Valencia, 2013) Kc values from FAO (Allen, Pereira, Raes, & Smith, 1998)
Rain events table	IWMI Water atlas (http://wcatlas.iwmi.org): Coordinates: -75.8; -12.5
Threshold flow accumulation	800
$\alpha_m, \beta_i, \gamma$	Default (1/12; 0; 1)

*This input changes for each scenario (CN and Kc values change according to Table 2)

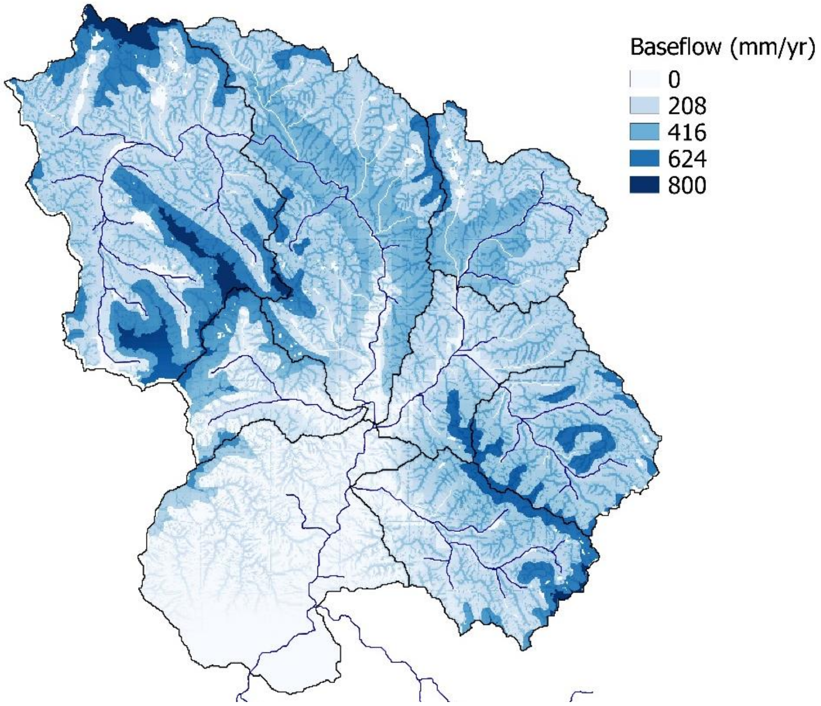

Figure A1: Baseline baseflow estimates from the SWAT and InVEST models for the Cañete watershed.

A2. Sediment retention model

Inputs to the InVEST sediment retention model are summarized in Table A2. Sediment export estimates are illustrated in Figure A2, showing general patterns that match those of previous studies (Francesconi et al., 2018). The model was not calibrated for lack of local sediment data.

Table A2: Sediment retention model parameters sources and values

Name	**Source**
DEM	CGIAR-CSI SRTM (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1)
Erosivity layer	Precipitation from WorldClim (Hijmans et al., 2005). Relationship between erosivity and precipitation from Roose (Roose, 1996)
Erodibility layer	Peru National Office of Natural Resource Evaluation (ONERN)
LULC	Peru National Geographic Institute (IGN)
Threshold flow accumulation	800
Biophysical table* (C and P factors)	C and P factors from InVEST database (https://www.naturalcapitalproject.org/invest/)

*This input changes for each scenario (CN and Kc values change according to Table A4)

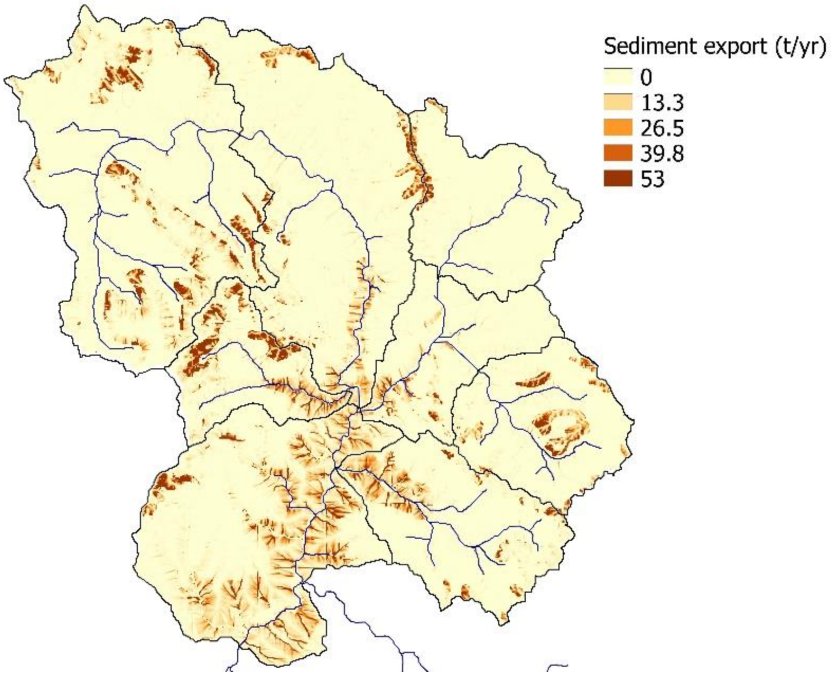

Figure A2: Baseline sediment export estimated by the InVEST model for the Cañete watershed.

A3. Modeling the effect of grazing management

Grazing effects on hydrological processes include decreased interception of precipitation, soil compaction, and potentially decreased evapotranspiration. The magnitude of these effects depends on soil and vegetation, climate (frequency and intensity of rain events), as well as animal types and past land management (NRCS-USDA, 2003). To model hydrologic response to grazing, researchers typically use empirical hydrologic models (Dunne, et al., 2011; Fiedler, et al., 2002; Zhao et al., 2010). A common approach is described in the USDA National Range and Pasture handbook (NRCS-USDA, 2003), based on quantitative relationships between Curve Numbers and grazing intensity (defined as percentage of ground cover or qualitative grazing intensity). Empirical models show high levels of uncertainty, an issue that can be addressed by testing several plausible levels of soil compaction (Fatichi, et al., 2014). To inform the parameterization of the model used in this study, we reviewed the empirical evidence of the effect of grazing on hydrologic processes with a regional focus on the Andes.

Literature on the effect of grazing intensity on runoff and soil properties is surprisingly scarce and indicates mixed responses (e.g. Trimble and Mendel (1995) and Gifford and Hawkins (1978)). While an increase in runoff and non-linear responses is common (Fatichi et al., 2014; Savadogo, et al., 2007), empirical studies show a large variability in the effects of grazing on runoff or infiltration rates, which can be unnoticeable (Dunne et al., 2011; Mapfumo, et al., 2004; Wine, et al., 2012). Empirical studies consistently show an increase in soil loss with grazing intensity, often with a non-linear effect (Dunne et al., 2011; Mwendera & Saleem, 1997; Trimble & Mendel, 1995; Warren, et al., 1986); although Wine et al. (2012) did not observe any effect on soil loss. Bilotta et al. (2007) provide a review of the evidence of the effect on soil properties, vegetation, and water quality, showing a great variability in response.

These general trends hold in the Andes, where researchers note a large variability in hydrologic responses to land use change and grazing practices (Buytaert et al., 2006). Crespo et al. (2011) did not find significant hydrologic effects of human impact, probably because of the relatively low grazing intensity (2-3 animals per hectare). Ochoa-Tocachi et al. (2016) suggest that only “high intensity” grazing (no definition of the practice) affects runoff coefficients (increase) and infiltration capacity (decrease). A study by Harden et al. (2013) did not find any significant effect on soil hydrology by alpacas, an endemic Andes grazer. This supports the general belief that hooved animals (cattle) have higher impact on hydrologic processes due to higher compaction levels. With regards to evapotranspiration, puna/paramo evapotranspiration rates are relatively low (0.8-1.5 mm/day, Buytaert et al., 2006) and possibly unaffected by grazing. This is due to two compensatory effects: on one hand, evapotranspiration in grazed areas may increase due to regrowth of vegetation and reduced shading, while on the other hand, evapotranspirative demand is lower due to lower amount of aboveground biomass (Buytaert et al., 2006).

B. Rangeland production model

General model description

The rangeland production model consists of two dynamic and interacting submodels: a pasture production submodel and a herbivore diet and digestion submodel. The pasture production submodel is the Century model (version 4.6, Parton, et al., 1988); this model uses climate and soils data to predict grass growth. The herbivore submodel simulates diet selection from among the available grass types and conversion of the selected diet to energy for maintenance and growth. The herbivore diet and physiology model is adapted from GRAZPLAN (Freer, Moore, & Donnelly, 2012). While the Century 4.6 executable is called as-is from the rangeland production model, only selected aspects of the GRAZPLAN herbivore physiology model were adapted. These selected subprocesses and parameters were transcribed from values and equations published by Freer et al. (2012).

Model inputs are listed in Table A3. The model is “point-based” with all units being per hectare, so it can be interpreted to represent the dynamics of one ha of pasture. The timestep of the model is one month, enforced by the monthly time step of the Century model; daily forage intake and weight change calculated by the ruminant physiology submodel are multiplied by the number of days in the given month to match this timestep. The model produces a time series as output which contains, for each time step, the biomass of each grass type and animal type, the offtake selected by each animal type, and the weight gained or lost by each animal type in that timestep.

Grass types, representing forage resources, are model entities: each grass type is characterized by a set of Century parameters describing its growth pattern, response to stress, etc. (Table A3). Century reports aboveground live and standing dead vegetation at each time step. Because these are expected to be of greatly different nutritional value for herbivores (Coleman & Moore, 2003), live and dead portions of each grass type are characterized by different quality parameters. The live and standing dead biomass fractions are each characterized by their current biomass (kg/ha), dry matter digestibility (DMD; %), and crude protein content (%). The biomass and crude protein content of each forage class fluctuate at each model step as the grass grows and is consumed by herbivores.

The livestock herd is composed of one or multiple age/sex classes, and each age/sex class is a model entity characterized by its breed, average age (days), average weight (kg), sex, castrate status (if male, either castrate or entire), weight at birth (kg), and standard reference weight (kg; Table A3). The standard reference weight (cf. Freer et al. 2012) is the weight of a mature female in median condition and varies by breed. During the course of a model run each herbivore class will age and may gain or lose weight, while its other state variables remain constant.

At each monthly time step, the rangeland production model calls Century to predict nutrient cycling, fall of standing dead biomass, and growth of new biomass (see Parton et al. (1988) for detailed description of the Century model). Given the reported biomass and crude protein content of the forage, the animal diet selection submodel simulates selective feeding by herbivores and predicts how much of live and standing dead forage is consumed by the animals. The selected diet is then allocated to maintenance and growth, following equations 31-56, 77-81, 101-117 in Freer et al. (2012).

Century includes pre-parameterized grazing events that impact ecosystem function through removal of live and dead biomass, return of nutrients to the soil via feces and urine, alteration of the root:shoot ratio, and altered N content of live shoots and roots (Holland, Parton, Detling, & Coppock, 1992). After the diet selection submodel completes, forage offtake by herbivores is formatted as a grazing event in Century using the removal of biomass calculated by diet selection so that impacts of grazing are reflected in forage growth in the next model step.

The simplified animal physiology submodel simulates the intake and performance of a representative individual animal for each age and sex class only, and does not simulate population-level processes such as births and deaths. For this reason, all simulated animals in a given age/sex class are assumed to be of equal age and do not undergo reproduction (Table A3). While this modeling choice means that the energetic costs of pregnancy and lactation are not included in allocation of the diet to liveweight gain, we believe it is appropriate to capture broad impacts of stocking density and duration on gain as a metric of animal performance.

Adaptation of the GRAZPLAN ruminant physiology model to New World camelids

The rangeland production model relies on diet selection and physiology submodels adapted from the GRAZPLAN model, which was developed for application to true ruminant animals, i.e., cattle and sheep. To run the model for camelids, we adjusted model parameters from default values given for sheep. While there is some evidence that diet selection and digestive physiology of New World camelids differs somewhat from that of true ruminants, these differences are not well understood (Esteban & Thompson, 1988; Wuliji et al., 2000). Modifications to the rangeland production model to account for the differing physiology of camelids follow comparisons with sheep and cattle reviewed by Van Saun (2006). These changes are reduction of maximum potential intake by 30% relative to sheep, and reduction of the energy and protein requirement of maintenance by 27% and 26%, respectively, relative to sheep (Van Saun, 2006).

Model set-up and spin-up simulations

Table A3 provides the detailed description of the input data and sources. The output of interest, liveweight gain per unit intake, is highly sensitive to animal size (Kowal, unpublished data). Because data to calibrate animal weight gain in the region were not available, while we had confidence in characteristic animal weights for each animal species (Table A3), we chose to reset animal weight to its initial value at the beginning of each monthly time step after recording liveweight gain in that month. This allowed us to avoid propagation of uncertainty in liveweight gain to forage offtake and biomass dynamics.

The rangeland production model implements a simplified animal physiology submodel that simulates the intake and performance of a representative individual animal only, and does not simulate population-level processes such as births and deaths. For this reason, all simulated animals are assumed to be of equal age and do not undergo reproduction (Table A3). While this modeling choice means that the energetic costs of pregnancy and lactation are not included in allocation of the diet to liveweight gain, we believe it is appropriate to capture broad impacts of stocking density and duration on gain as a metric of animal performance.

The Century model requires a “spin-up” simulation of several thousand years to establish soil organic matter levels at equilibrium. During this time, a historical management schedule must be supplied. We used a site management history similar to that used by Parton *et al.* (1993) for a high-elevation C3 grassland, containing light grazing during the five months of the rainy season (November through March). We assumed that each subwatershed experienced this management history. The pre-parameterized light grazing level included with CENTURY specifies removal of 10% of live plant material and 5% of standing dead plant material by herbivores each month. Climate drivers for this spin-up period were averaged from the 17 years of empirical weather station data used to drive each subwatershed.

Table A3: Data sources for inputs to the rangeland production model. SRW: standard reference weight, the weight of a mature female animal in median condition; SFW: standard fleece weight, the average weight of fleece.

Data group	Data type	Description	Source
CENTURY drivers	Climate	Monthly temperature and precipitation	Daily weather data collected by Servicio Nacional de Meteorología e Hidrología (SENAMHI).
	Soil	Composition, bulk density, pH	(ISRIC, 2013)
CENTURY parameters	Fix file	Mesic grassland	Parameters given in Parton *et al.* 1993 for shortgrass prairie (Central Plains Experimental Range, Colorado)
	Template site	C3 grassland	Parameters given in Parton *et al.* 1993 for shortgrass prairie (Central Plains Experimental Range, Colorado)
	Grass type	C3 grass	Parameters given in Parton *et al.* 1993 for mesic C3 grassland (Khomutov, Ukraine)
	Historical management	C3 grassland	Light grazing (removal of 10% of live and 5% of standing dead) during months 11, 12, 1, 2, 3 (Parton et al. 1993)
Grass description	Digestibility of green	65%	(Bartl et al., 2009), (Reiner, 1985)
	Digestibility of standing dead	32.5%	Half that of green
	Crude protein of green	10.2%	(Bartl et al., 2009), (Reiner, 1985)
	Crude protein of standing dead	5.1%	Half that of green
Cattle herd	Herd composition	7% bulls, 93% cows	Household surveys
	Initial age	2 years	Age at maturity
	Initial weight	508 kg	Standard reference weight for herd composition and age
	Breed	*B. taurus*	(FAO, 2000): Simmental and Brown Swiss predominate
	SRW	650 kg	(CSIRO, 1990) (Simmental breed)
	Birth weight	40.3 kg	(Herring, undated)
Sheep	Initial age	1.5 years	(Burfening & Chavez, 1996)
	Initial weight	26.5 kg	Same as standard reference weight
	SRW	26.5 kg	(Burfening & Chavez, 1996)
	Birth weight	3 kg	(Burfening & Chavez, 1996)
	SFW	3.32 kg	(Burfening & Chavez, 1996)
Camelids	Initial age	3 years	(Wuliji et al., 2000) (Huacaya alpacas)
	Initial weight	72.1 kg	Same as standard reference weight
	SRW	72.1 kg	(Wuliji et al., 2000)
	Birth weight	8.4 kg	(Bustinza, Burfening, & Blackwell, 1988)
	SFW	1.81 kg	(Bustinza et al., 1988)
Return of consumed nutrients in urine and feces	Fraction of consumed C returned	0.3	(Parton et al., 1993)
	Fraction of consumed N returned	0.8	(Parton et al., 1993)
	Fraction of consumed P returned	0.95	(Parton et al., 1993)

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