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Application of the MODIS MOD 17 Net Primary Production product in grassland carrying capacity assessment

Jan de Leeuw[a,*], Afag Rizayeva[a,g], Elmaddin Namazov[b], Emil Bayramov[c], Michael T. Marshall[d], Jonathan Etzold[e], Regina Neudert[f]

[a] Baku State University, Dept. Bioecology, AZ1148, Baku, Azerbaijan
[b] GIZ, Integrated Biodiversity Management South Caucasus, Baku, Azerbaijan
[c] BP Azerbaijan-Georgia-Turkey Region, Baku, Azerbaijan
[d] Faculty Geoinformation Science & Earth Observation, University Twente, Enschede, the Netherlands
[e] ESTOK UG, Bernau, Germany
[f] Greifswald University, Faculty of Law and Economics & Institute of Botany and Landscape Ecology, Greifswald, Germany
[g] SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI 53706, USA

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ABSTRACT

Remote sensing based grassland carrying capacity assessments are not commonly applied in rangeland management. Possible reasons for this include non-equilibrium thinking in rangeland management, and the costliness of existing remotely sensed biomass estimation that carrying capacity assessments require. Here, we present a less demanding approach for grassland biomass estimation using the MODIS Net Primary Production (NPP) product and demonstrate its use in carrying capacity assessment over the mountain grasslands of Azerbaijan. Based on publicly available estimates of the fraction of total NPP partitioned to aboveground NPP (fANPP) we calculate the aboveground biomass produced from 2005 to 2014. Validation of the predicted aboveground biomass with independent field biomass data collected in 2007 and 2008 confirmed the accuracy of the aboveground biomass product and hence we considered it appropriate for further use in the carrying capacity assessment. A first assessment approach, which allowed for consumption of 65% of aboveground biomass, resulted in an average carrying capacity of 12.6 sheep per ha. A second more realistic approach, which further restricted grazing on slopes steeper than 10%, resulted in a stocking density of 6.20 sheep per ha and a carrying capacity of 3.93 million sheep. Our analysis reveals overgrazing of the mountain grasslands because the current livestock population which consists of at least 8 million sheep, 0.5 million goats and an unknown number of cattle exceeds the predicted carrying capacity of 3.93 million sheep. We consider that the geographically explicit advice on sustainable stocking densities is particularly attractive to regulate grazing intensity in geographically varied terrain such as the mountain grasslands of Azerbaijan. We further conclude that the approach, given its generic nature and the free availability of most input data, could be replicated elsewhere. Hence, we advise considering its use where traditional carrying capacity assessments are difficult to implement.

1. Introduction

Carrying capacity is a concept used to regulate stocking density and avoid overgrazing by livestock (Stoddart et al., 1975). It has been defined as “the density of cattle providing the maximum sustained production of beef” (MacNab, 1985) or more generally “the maximum population of a given species that can be supported indefinitely in a defined habitat without permanently impairing the productivity of that habitat” (Rees, 1996). In grassland management, it relates to the number of livestock per unit area that can be sustained given the amount of available forage and is expressed as the number of animals and days that an area of land may be grazed. It is calculated from estimates of the above ground biomass, the fraction of that biomass that can be grazed sustainably (proper use factor) and the livestock’s daily food requirements.

While simple to define, the implementation of carrying capacity assessments is demanding because the production of forage varies in space and time. Given this, in areas with large year-to-year variation in

* Corresponding author at: ISRIC World Soil Information, PO Box 353, 6700, AJ Wageningen, the Netherlands.
E-mail addresses: jan.deleeuw@wur.nl (J. de Leeuw), rizayeva@wisc.edu (A. Rizayeva), el.namazov@gmail.com (E. Namazov), emil.bayramov@yahoo.com (E. Bayramov), m.t.marshall@utwente.nl (M.T. Marshall), etzold@estok.de (J. Etzold), regina.neudert@uni-greifswald.de (R. Neudert).

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biomass production, the carrying capacity may need to be adjusted annually. Recommended stocking rates are typically fixed for a whole ranch or an entire country, which may result in under- or over-exploitation of available resources in heterogeneous landscapes. In such situations, a geographical differentiation of carrying capacity would allow a better exploitation of the pasture resources (Neudert et al., 2013).

The carrying capacity concept is a Malthusian view (Malthus, 1798) of a grazing system. It assumes a grazing system in which livestock populations are allowed to grow faster than and exceeding equilibrium with the available forage resources, resulting in overexploitation with rangeland degradation as a result (Hardin, 1968). Following theoretical work by DeAngelis and Waterhouse (1987), a paradigm shift occurred towards considering drylands grazing systems as non-equilibrium rather than equilibrium systems (Ellis and Swift, 1988; Behnke and Scoones, 1993; Vetter, 2005). According to this paradigm, drylands grazing systems are non-equilibrium systems, where volatile rainfall and primary production prevents livestock populations overshooting the equilibrium with their forage resources and overstocking and range degradation are unlikely to occur.

As a result, some consider carrying capacity based rangeland management inappropriate for use in drylands grazing systems because of the assumed non-equilibrium nature of these systems (e.g. Scoones, 1995; Niamir-Fuller, 1999). Others however, have suggested that the difficulty to confirm a rangelands' equilibrium status has resulted in applying the non-equilibrium paradigm to much wider geographies than appropriate (Fernandez-Gimenez and Allen-Diaz, 1999; De Leeuw et al., 2019). Despite this controversy, carrying capacity assessments are nowadays little used in drylands in most parts of the world because of persistent advocacy in favor of the non-equilibrium paradigm. This is a missed opportunity, because carrying capacity assessments remain a conceptually appealing and useful management tool in equilibrium grazing systems.

In such grazing systems, remote sensing could be applied to support carrying capacity assessments with the estimation of biomass that such assessments require. Reeves et al. (2015), who reviewed available remote sensing methods in rangeland management and carrying capacity assessment distinguished empirical models and semi-empirical approaches for estimation of aboveground biomass. The empirical approach was pioneered by Tucker et al. (1983) and Tucker (1985) who predicted biomass through the inversion of statistical models describing the relationship between remote sensing vegetation indices and field based biomass estimates (See also Liu et al., 2017, 2015; Yu et al., 2010). The second approach consists of coupled empirical and process-based models. For example, Hunt and Miyake, (2006) coupled empirical biomass estimates derived from MODIS NDVI to feed into a process-based model for gross (GPP) and net (NPP) primary production to calculate the biomass available to animals. Similarly, the Livestock Early Warning System (LEWS) implemented in Africa (Stuth et al., 2005) and Mongolia (Angerer, 2012) fed biomass estimates derived from MODIS NDVI into the process-based Phytomass Growth Simulation Model to predict available forage.

Obviously, remote sensing has potential to support carrying capacity assessments and it would be ideal if in equilibrium grazing systems the technology could be implemented to support more sustainable livestock and grassland management in dryland ecosystems. Yet, to our knowledge, the above approaches have not been widely adopted and implemented for managing stocking rates and grasslands. Reasons may include the controversy over the non-equilibrium paradigm, the labor intensity and the technical expertise required for remotely sensed carrying capacity assessments and the observation that these methods perform poorly when transferred to other regions (Eisfelder et al., 2012).

Another approach would be to model carrying capacity based on remotely sensed estimates of net primary production (NPP). Eisfelder et al. (2014) for example parametrized the BETHY/DLR model to predict NPP for Kazachstan. While the BETHY/DLR approach predicted NPP for the area for which it was parametrized (i.e. Kazachstan), the MODIS gross (GPP) and net (NPP) primary production products (Running et al., 2004; Zhao et al., 2005) predict primary production for the entire globe. The MODIS MOD17 product calculates GPP, or photosynthesis, based on fAPAR, derived from remote sensing, which is fed into a light use efficiency photosynthesis model (Haxeltyne and Prentice, 1996; Hilker et al., 2008). The algorithm also estimates maintenance and growth respiration of the vegetation, which when subtracted from GPP yields NPP. MOD17 delivers estimates of GPP and NPP on an eight day basis, which are aggregated to monthly and annual time scales. This approach has been used by Reeves et al. (2006) who compared MODIS NPP to field estimates of peak biomass from grasslands in Oklahoma and concluded that MODIS vegetation productivity estimates are suited for regional grassland studies.

Despite the promising results from Reeves et al. (2006), MODIS NPP has never been used to estimate grassland carrying capacity. One of the reasons for this is that the MODIS NPP product measures NPP that is allocated to above and belowground biomass, while an estimate of aboveground biomass is needed for a carrying capacity assessment. A carrying capacity model thus needs to account for the fraction of the total NPP that is partitioned to above (fANPP) and belowground (fBNPP) biomass. Hui and Jackson (2005) analyzed a dataset of above and belowground NPP estimates in grasslands around the world. Their analysis revealed that mean annual temperature (MAT) was the single best predictor of fBNPP in grasslands, while the addition of mean annual precipitation (MAP) did not further improve the results. This knowledge on drivers of grassland fBNPP could be combined with the MODIS NPP product to derive an estimate of aboveground NPP for use in carrying capacity assessments. To the authors' knowledge, there has been no attempt to assess grassland carrying capacity using this approach.

The objective of this paper is to describe a novel approach to assess grassland carrying capacity based on an aboveground grassland biomass estimate derived from a combination of the MODIS MOD17 Net Primary Production Product and the fraction of NPP allocated to aboveground biomass that was derived from mean annual temperature and demonstrate its application to the mountain grasslands of Azerbaijan.

2. Methods

2.1. Modelling aboveground biomass as an input to a carrying capacity assessment

The approach taken to model carrying capacity is presented schematically in Fig. 1. First we predicted above ground biomass (AB) based on the MODIS Net Primary Production (NPP) Product MOD17A3H (Running and Zhao, 2015; Running et al., 1999). The MODIS NPP values, which are expressed in kg C m^{-2} yr^{-1}, were converted to biomass using a biomass to carbon conversion factor of 0.47 (IPCC et al., 2006). Next, Aboveground Biomass (AB) was derived from NPP, using the fraction of NPP that is allocated to above ground biomass (fANPP).

$$AB = NPP \times fANPP$$

We used the equation given by Hui and Jackson (2005)

$$fANPP = 0.171 + 0.0129\ MAT$$

where MAT = mean annual temperature in °C. We downloaded the 1 km^2 interpolated climate data for the period 1970–2000 from Worldclim version 2 (Fick and Hijmans, 2017) and derived fANPP from MAT. The processing of the MODIS MOD17 data and further GIS modeling was implemented in Q-GIS and ArcGIS. The above conversion of NPP to AB assumes that the aboveground biomass reflects the NPP. This is a reasonable assumption in grassland ecosystems where biomass

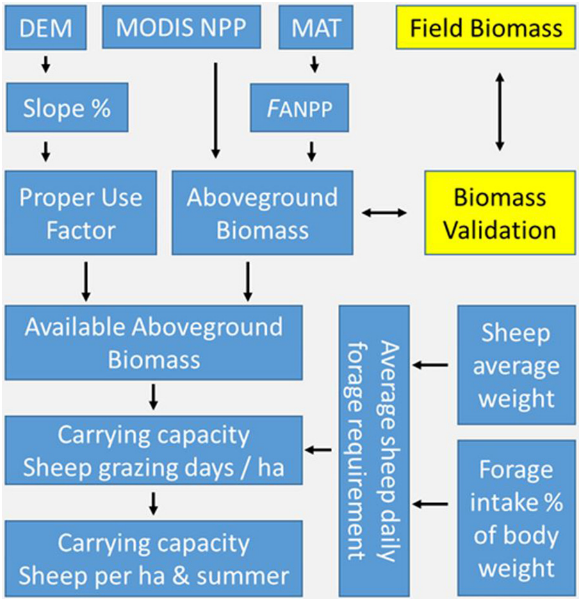

Fig. 1. Steps in modeling carrying capacity used in this study. DEM = digital elevation model, MAT = mean annual temperature, F_{ANPP} = fraction of NPP allocated to aboveground NPP.

dies off in winter or during the dry period. In such cases, the accumulated biomass or standing crop is the result of the current years' NPP allocated to aboveground biomass.

The calculation of aboveground biomass is the generic part of the carrying capacity assessment and can be applied globally. The other inputs in the carrying capacity assessment, the proper use factor and the animal forage requirements, are system specific and need to be parametrized separately for each area.

The remainder of the methods chapter is structured as follows. Section 2.2 presents the study area where the carrying capacity assessment was implemented. Section 2.3 describes the procedures used for an independent validation of the aboveground biomass estimates. Finally, Sections 2.4 and 2.5 describe the parametrization of the proper use factor and the daily forage requirements respectively.

2.2. Study area

The above carrying capacity assessment approach was applied to the mountain grasslands of Azerbaijan, a country situated in the Southern Caucasus (Fig. 2). The country has varied topography with elevation ranging from 28 m below to 4446 m above sea level (m a.s.l.).

Transhumant livestock keeping is the major livestock production system, which coexists with mostly small scale sedentary livestock production systems. Every year, several million sheep, goats and young cattle migrate between the 0.6 million ha of summer pastures in the mountains and 1.78 million ha of winter pastures in the semi-arid lowlands (Kosajev and Guliev, 2006). The summer pastures, which are the focus of this study, are situated between 1600 and 3500 masl, which corresponds to the sub-alpine, the alpine and the sub-nival zone (Table 1). The vegetation consists of grassland, shrubland and open vegetation in the alpine and sub-nival zone and secondary grasslands and xeric steppes in the sub-alpine zone (Zazanashvili et al., 2000).

While the number of animals that migrate between the winter and summer pastures is not recorded separately, there are annual statistics on the total livestock numbers in the country. The total animal numbers steadily increased over the years reaching approximately 8 million heads of sheep, 0.5 million goats and 2 million cattle by January 1st 2016 (Fig. 3). Virtually all small stock (i.e. sheep and goats) migrates between the summer and winter pastures. The figure does not however reveal any volatility in the populations of small stock and hence we conclude that the pastoral systems of Azerbaijan are equilibrium systems for which carrying capacity assessment is an appropriate management tool. Further evidence that the grazing lands of Azerbaijan are equilibrium systems was given by Neudert (2015) who reported that the coefficient of variation of annual rainfall in winter and summer pastures remains below the 33% that has been proposed (Ellis, 1994) as a threshold differentiating equilibrium and non-equilibrium systems.

The actual number of livestock that migrates to and resides in the summer pastures is larger than what is shown by these statistics. This is because livestock population censuses are carried out in the first week of January before the lambs are born in late winter. At this time, livestock populations reach their annual low and consequently in summer animal numbers are higher than what official statistics suggest.

Kosajev and Guliev (2006) reported that the high number of animals cause overgrazing which negatively affects the quality and productivity of the summer pastures. The resolution "Rules on allocation and use of pastures, commons and hayfields" (Government of Azerbaijan, 2000), is the response of the government to manage this overgrazing through regulation of stocking densities. It prescribes permissible stocking densities per hectare ranging from 1 to 4 small stock (sheep and goat) for winter pastures, 2–8 small stock for summer pastures and 2–3 and 4–6 small stock for non-irrigated and irrigated hayfields respectively. Kosajev and Guliev (2006) recommended for summer pastures 3–7 animals per hectare depending on grassland condition.

It is difficult to implement the above stocking densities, because they are given as ranges with the advice to adjust to specific situations depending on grassland condition. Neudert et al. (2013) stressed the need to differentiate stocking rates geographically more precisely to allow a better exploitation of pasture resources and prevent overexploitation. Etzold and Neudert (2013) provided guidelines for monitoring the summer pastures and calculating the carrying capacity. Yet, so far there is no geographically explicit advice on the permissible stocking density for the mountains of Azerbaijan.

2.3. Validation of the above ground biomass estimates

To calculate above ground biomass for the grasslands in the mountains of Azerbaijan we downloaded tiles H21V04 and H21V05 of MOD17A3H (annual NPP) for 2005–2014 from the USGS LP DAAC website (Table 2) and calculated aboveground biomass according to the procedures explained in Section 2.1.

As a next step, we assessed the performance of predicting ANPP while comparing the reported above ground biomass measurements collected in 2007 and 2008 from 17 livestock exclosures and hay fields in the Shahdag area of north-eastern Azerbaijan (Neudert et al., 2013) with the ANPP predicted by our model for the same year and same sites. Standing crop was clipped from 1 m^2 quadrats, dried and weighed.

The sample of field biomass estimates was drawn from a sampling universe consisting of relatively densely vegetated grasslands. The wider landscape also consisted of degraded grassland, bare soil and rock outcrops. The average biomass of this wider landscape therefore will be lower than the average biomass of the grasslands that were sampled. Not surprisingly, we observed as reported later on, that the average biomass collected in the field was higher than the MODIS based aboveground biomass estimates.

The following method was used to correct the overestimation of landscape level productivity by the field biomass estimates and allow comparison of the two data sets. We downloaded and calculated NDVI for the Landsat TM image path 167 and row 031 of 20.08.2007 and 05.07.2008 that covered the grasslands in the Shahdag area in the alpine and subalpine zones of the Greater Caucasus. Next, we extracted the NDVI values for the Landsat pixel where the biomass data had been collected in the field as well as the average NDVI for the corresponding 25 ha MODIS pixel. Based on these two values we calculated the ratio of the NDVI of the MODIS pixel and the Landsat pixel and used this ratio

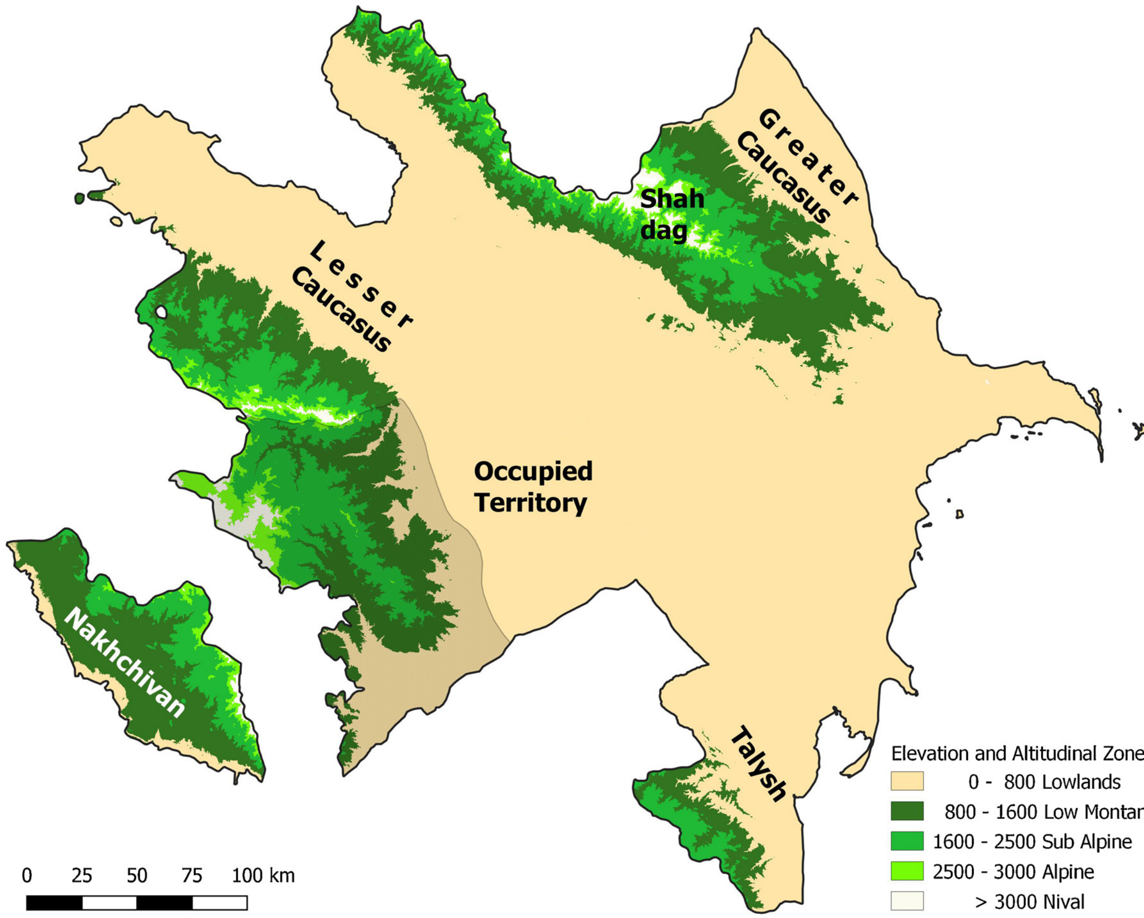

Fig. 2. Map of altitudinal zones (m a.s.l.) of Azerbaijan with occupied territory in shaded grey.

Table 1
Elevation range of the summer pastures and the vegetation zones in there.

Vegetation zone	Elevation range	Source
Summer pastures	1600–3500 m a.s.l.	Kosajev and Guliev, 2006
Sub-alpine zone	1600–2500 m a.s.l.	Zazanashvili et al., 2000
Alpine zone	2500–3000 m a.s.l.	Zazanashvili et al., 2000
Sub-nival zone	3000–3500 m a.s.l.	Zazanashvili et al., 2000

to adjust the field biomass to an adjusted field biomass estimate for the 25 ha MODIS pixels. We then evaluated the accuracy of the MODIS based ANPP predictions while comparing the adjusted field biomass estimates against the MODIS ANPP estimates for the same pixel and year.

Finally, and following the above evaluation of the accuracy ANPP predictions for 2007 and 2008, we calculated the ten-year average NPP, for the period 2005 to 2014 and next calculated the average annual ANPP for the same period following the procedures described above. Part of the area is covered by forest rather than grassland. We downloaded the Landsat Tree Cover Product (Sexton et al., 2013), which provides an estimate of the percentage canopy cover of trees greater than 5 m for the year 2000 from the Global Land Cover Facility. Preliminary analysis revealed that pixels with trees in our mountain sites were either densely forested or having relatively low tree cover. We used this tree cover product to exclude the densely forested areas and excluded all areas with tree cover above 50% from the analysis. This left a few areas with isolated trees and areas with stunted *Betula* trees (Krummholz) included in the grassland pixels.

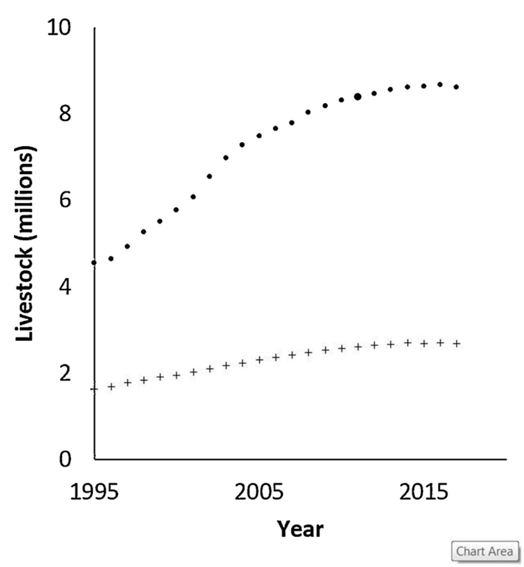

Fig. 3. Number of livestock (● = sheep and goat; + = cattle) in Azerbaijan, 1995–2017 (Source Azstat, 2017).

2.4. Proper use factor and calculation of available forage

We then modelled the available fodder (AF, in kg per ha) of the summer pastures using the equation

$AF = ANPP \text{ x } F_{pu}$

where ANPP is the above ground NPP and F_{pu} is the proper use factor.

Table 2
GIS and field data and model parameters used in modelling above ground biomass and carrying capacity.

Data or parameter	Value and measurement unit	Source
GIS and field data		
Boundaries, road and water infrastructure		Open street map
Elevation 90 m SRTM DEM	m a.s.l.	SRTM
Annual Net Primary Production (NPP)	kg C ha^{-1} yr^{-1}	LP DAAC MOD17A3H
Mean Annual Temperature (MAT)	°C	Fick and Hijmans, 2017
Georeferenced Biomass Estimates	dry weight, kg ha^{-1}	Etzold and Neudert, 2013
Forage supply modelling		
Conversion factor of biomass to carbon	0.47	IPCC 2006
Relation fANPP and MAT	fANPP = 0.171 + 0.0129 MAT	Hui and Jackson, 2005
Proper use factor	0.50	George and Lyle, 2009
Reduction proper use factor for slopes 11-30%	30%	George and Lyle, 2009
Reduction proper use factor for slopes 31-60%	60%	George and Lyle, 2009
Reduction proper use factor for slopes > 60%	100%	George and Lyle, 2009
Calculation feed requirements		
Live weight ewe (summer)	43 kg	Dadashov, undated
Live weight ram (summer)	63 kg	Dadashov, undated
Live weight lamb (summer)	25 kg	Dadashov, undated
Daily forage intake (% animal biomass)	2.5–3%	PIRSA, undated
Duration of residence in summer pastures	100–120 days	Kosajev and Guliev, 2006

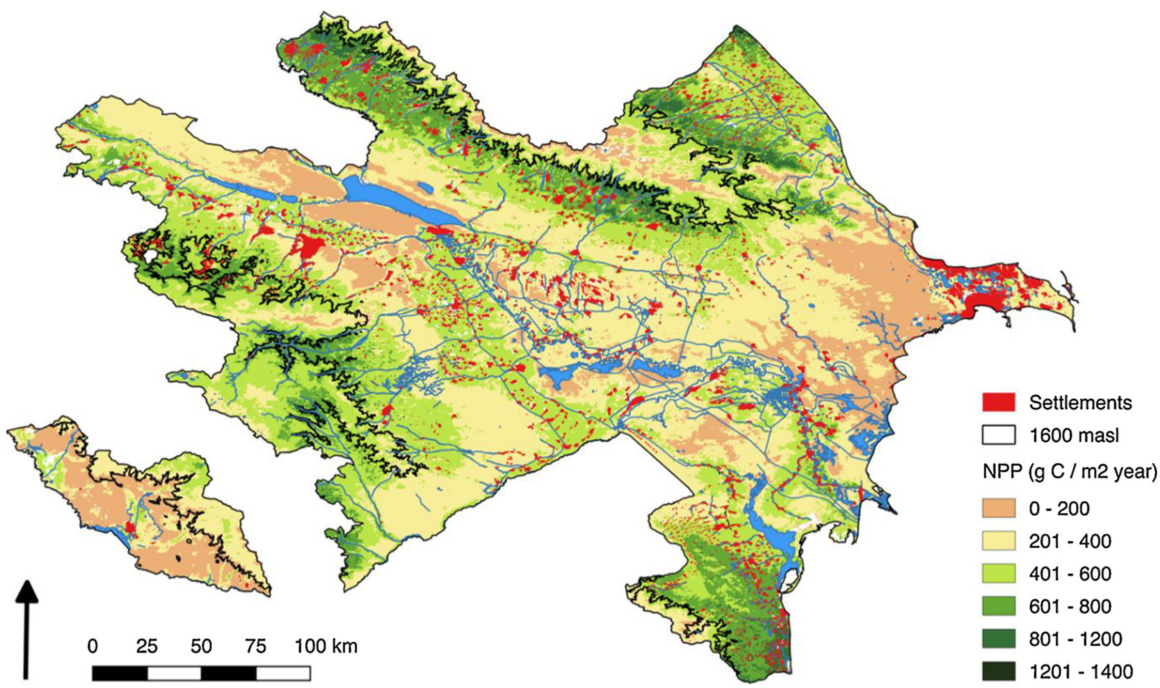

Fig. 4. Average annual net primary production (NPP, g C m^{-2} yr^{-1}) for 2005–2014 for Azerbaijan (Source MODIS17A3).

Not all aboveground biomass is taken up by livestock, because part is lost to other herbivores or by trampling and mixing with faeces. Further, it is advisable to leave some biomass to cover and protect the ground against erosion and to allow the vegetation allocating resources for regrowth during the next growing season. For these reasons a proper use factor is used in carrying capacity models to prescribe the fraction of the above ground biomass that can be grazed sustainably. We used a proper use factor of 0.65 used before in alpine systems in Switzerland (Mayer et al., 2005), France (Bornard and Dubost, 1992) and Azerbaijan (Neudert et al., 2013). This is somewhat higher than the 0.50 used in alpine systems in California (George and Lyle, 2009) and northern Pakistan (Sardar, 2003).

The above proper use factor is based on consideration of biomass availability alone. It does not consider the need to preserve a higher fraction of the above ground biomass for erosion control on steeper slopes. To account for this, the proper use factor was further adjusted downward on sloping lands following recommendations of George and Lyle (2009) by 0%, 30%, 60% and 100% for terrain with slopes of 0–10%, 11–30%, 31–60% and > 60% respectively. We downloaded the 90 m resolution STRM digital elevation model (DEM), and calculated slope percentages to develop a 90 m resolution raster file representing the geographical variation in slope steepness correction to be applied to the 65% proper use factor.

2.5. Animal forage requirements and calculation of carrying capacity

As a final step, we calculated the carrying capacity in number of sheep per hectare that could be sustained given the available fodder. The weight of rams, ewes and lambs differ by breed. We calculated the average weight of rams, ewes and 6 month old lambs while averaging the weight given by Dadashov (undated) for the seven breeds known to migrate in the mountains. A typical herd of sheep in the summer pastures consists of 54% ewes of 43 kg, 43% lambs of 25 kg and 3% rams of 63 kg on average. This results in an average body weight per head of sheep of 36 kg. The daily dry matter intake of livestock varies from 2.5 to 3% of their body weight on average quality pasture to 2% on poor quality pasture (PIRSA undated, De Leeuw and Tothill, 1990). We applied an average daily forage intake of 2.5% of animal body weight, because from spring to late summer forage quality changes from good to poor. A sheep of 36 kg thus requires 108 kg of forage for the 120 days that the animals reside in the summer pastures. Carrying capacity was then expressed as the density of all sheep (including ewes, rams and lambs) per hectare for a 120 day period.

3. Results

3.1. Net Primary Production (NPP)

There is significant variation in average annual NPP across Azerbaijan (Fig. 4). NPP varies from below 200 g C m^{-2} yr^{-1} in semi-arid lowlands, 400 to 600 g C in irrigated lands around River Kura to 600–1400 g C in rainfed croplands and forests on the footslopes and slopes of the Greater and Lesser Caucasus. Above 1600 m asl NPP declines with elevation from around 600 g C m^{-2} yr^{-1} in the upper sub-alpine zone to below 200 g C m^{-2} yr^{-1} in the sub-nival zone.

Forests, which were excluded from further analysis, extend to 2000 m a.s.l. on steeper slopes of the Greater and the Lesser Caucasus, but there is significant non-forested land used for grazing on gentler slopes, e.g. in the eastern Greater Caucasus and the northwestern Lesser Caucasus (Fig. 5). Finally, forest is virtually absent from the sub-alpine zone in the Nakhchivan exclave, reflecting the drier conditions in this area.

3.2. Aboveground NPP

Fig. 5 reveals significant regional variation in ANPP in the mountain grasslands. The most productive grasslands with ANPP above 2400 kg of dry biomass per ha are on the gently sloping north facing slopes in the sub-alpine zone of the Lesser and Greater Caucasus. Productivity of sub-alpine grasslands in the drier eastern end of the Greater Caucasus is lower, as is the case in the dry Talysh and Nakhchivan mountains. Grassland production in the alpine zone equals $800-1600$ kg ha^{-1} in the Greater and Lesser Caucasus, but less in the drier Nakhchivan area. Finally, ANPP is less than 800 kg per ha in the sub-nival zone.

3.3. Validation of aboveground biomass predictions

The average aboveground biomass of the 17 quadrats sampled in the field of 2974 kg ha^{-1} was 38% and significantly higher than the average NPP of 2163 kg ha^{-1} that was predicted by the MODIS-based ANPP model (paired t-test, t = 2.43, d.f. = 16, $P_{2\text{-sided}} = 0.027$). Analysis of the Landsat NDVI revealed that the 30 m Landsat pixels corresponding to the field biomass sampling sites (Fig. 6) had on average a 20% and significantly higher NDVI than the average NDVI for the 500 m MODIS pixels (paired t-test, t = 2.16, d.f. = 16, $P_{2\text{-sided}} <$ 0.046). The difference in NDVI supports the idea that the biomass of the field sites exceeded that of the 25 ha MODIS pixels. A correction is therefore necessary before comparing biomass estimates derived from small areas to the prediction of the MODIS ANPP method. We used the ratios of NDVI for the single Landsat pixels where the field biomass was sampled and the average NDVI for the 25 ha MODIS pixels, to adjust the field biomass to represent the field biomass of the area covered by the 25 ha MODIS pixels. This adjustment brought the estimate for field

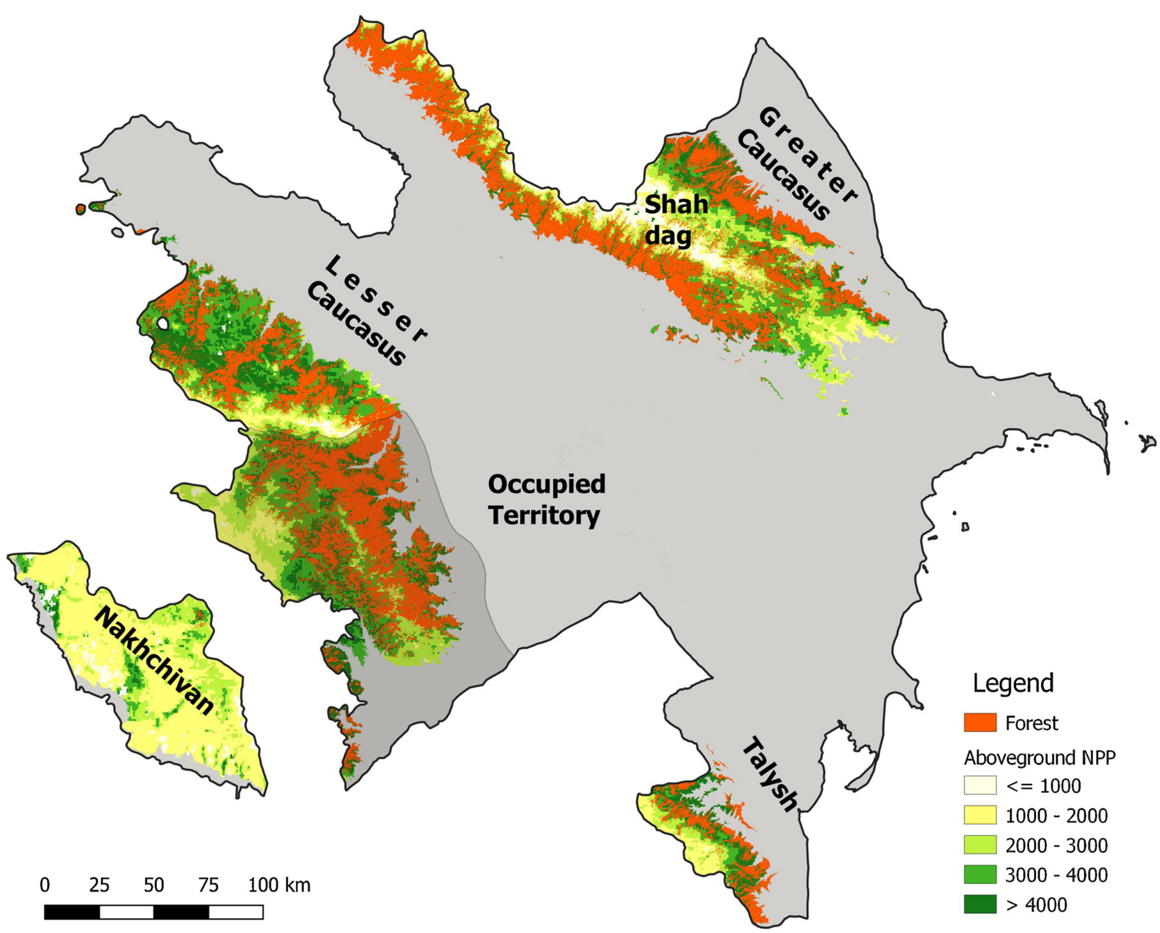

Fig. 5. Average annual aboveground net primary production (ANPP 2005–2014, kg. ha^{-1}.yr^{-1}) of grasslands situated above 1600 m a.s.l.

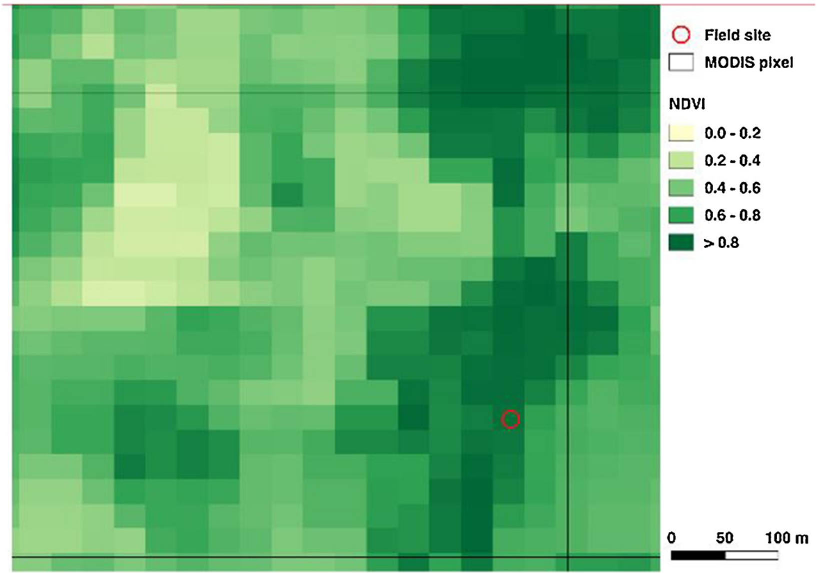

Fig. 6. Demonstration of the effect of scale of observation on productivity predicted by MODIS 17 and field-based data collection. Landsat 5 ETM path 167 row 031 date 05.07.2008 reveals that the plot where biomass was collected in the field had a higher NDVI (0.77) than the average NDVI (0.55) for the corresponding heterogeneous MODIS pixel.

biomass down to 2517 kg ha^{-1}. This was still 16% higher than the MODIS ANPP estimate of 2163 kg ha^{-1}. While after adjustment the difference was no longer significant at a critical value of $\alpha = 0.05$ (paired t test, $t = 1.90$, d.f. = 16, $P_{2\text{-sided}} = 0.076$), we nevertheless decided to avoid a possible bias and corrected the MODIS ANPP prediction upward to be as close as possible to the field-based measurements.

3.4. Proper use factor and livestock carrying capacity

Steep slopes characterize much of the summer pastures and there is little flat land (Fig. 7). Only a small fraction of the area has slopes below 10%. Most of the summer pastures, particularly the alpine and nival zones have steeper slopes and the proper use factor was reduced because of slope steepness. There is significant area in the Greater and Lesser Caucasus with slope steepness over 60%, which should not be grazed to avoid erosion.

Fig. 8 and Table 3 show the inferred carrying capacity in sheep per ha for the three altitudinal zones in the summer pastures of Azerbaijan. A proper use factor (PUF) that allows 65% of the above ground biomass being grazed irrespective of slope steepness results in a stocking density of sheep that can be sustained of 13.64 sheep per ha in the subalpine zone and 7.37 in the nival zone, while the carrying capacity for sheep, the number of animals that can be sustained, equals 8.05 million. However, when using a proper use factor (PUF) that considers slope steepness as well, the stocking density drops to 6.95 sheep per ha in the

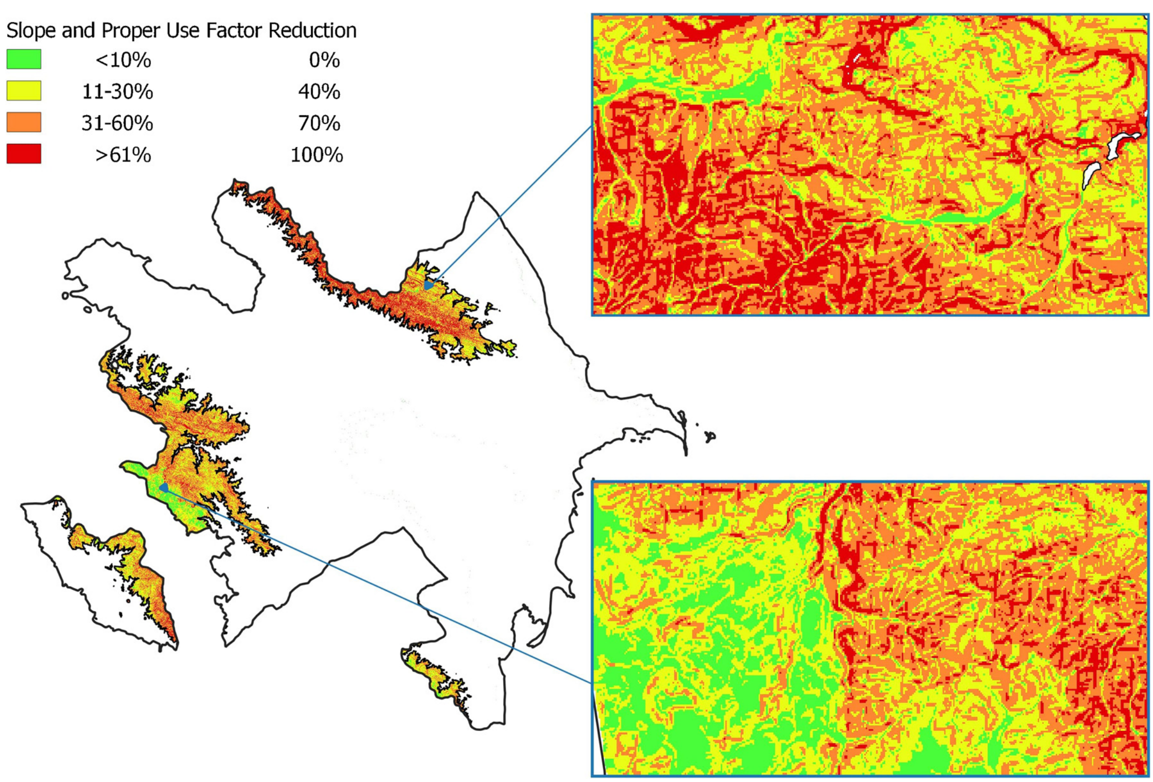

Fig. 7. Slope percentage classes and slope steepness related reduction of the proper use factor for summer pastures in the mountains of Azerbaijan.

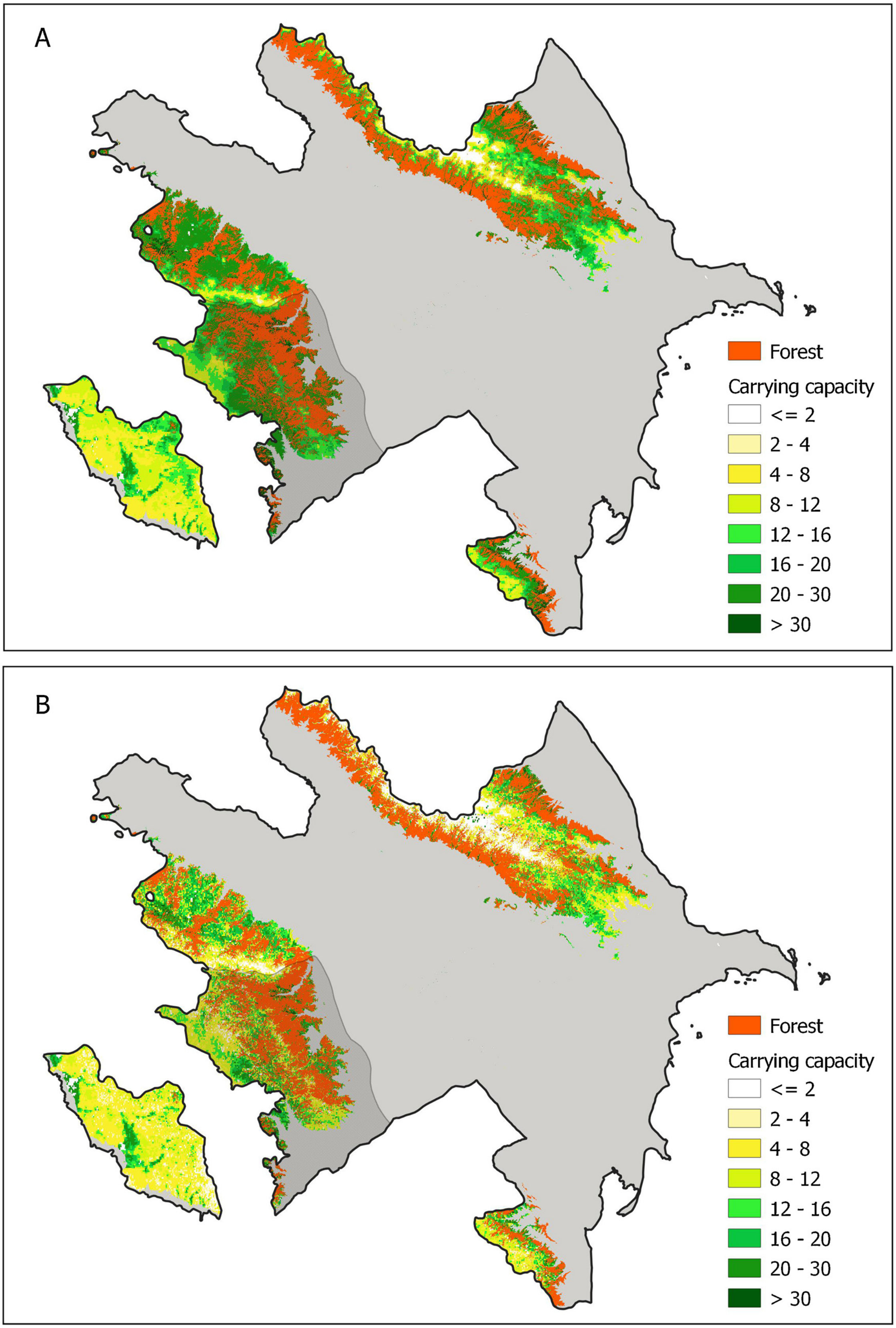

Fig. 8. Calculated carrying capacity for the summer pastures in Azerbaijan (Number of sheep per hectare that can graze sustainably during a 120 day period) according to two models that consider: A a Proper Use Factor (PUF) of 65%; B a PUF of 65% further reduced for slope steepness as in Fig. 7.

Table 3
Estimated sheep density (animal per ha) and total number of sheep (millions) that can be grazed in the entire summer pastures and for three vegetation zones under two carrying capacity models: a model (PUF) with a proper use factor (PUF) of 65% and a model (PUF + slope) that was further restricted according to slope percentage.

Zone	Altitude	Area	PUF 65%		PUF 65% and slope	
			Density	Total	Density	Total
Sub-alpine	1600–2500	4,99,575	13.64	6.81	6.95	3.47
Alpine	2500–3000	94,350	10.00	0.94	3.81	0.36
Nival	3000–3500	39,775	7.37	0.29	2.47	0.10
Summer pastures	1600–3500	6,33,700	12.70	8.05	6.20	3.93

subalpine zone to 2.47 sheep per ha in the nival zone. The carrying capacity under this more stringent scenario equals 3.93 million head of sheep.

4. Discussion

We presented a new approach to establish grassland carrying capacity based on the MODIS MOD17 NPP product. This deductive approach depends on an estimate of above ground NPP, which proved remarkably accurate as shown by validation of the ANPP predictions against independent biomass data from the field. The carrying capacity approach is easy to implement and less demanding than the empirical remote sensing approaches that have been used so far. Based on this, we conclude that the deductive carrying capacity model is attractive for implementation elsewhere.

There are however a few limitations to consider when wishing to implement this approach in a different place. A first limitation is that the approach described here is valid for grassland only. fANPP would need to be reparametrized when implementing the model in other rangeland types such as shrublands or wooded grasslands. A second limitation is that our model does not consider spatial variation in species composition, forage quality and palatability. The third and final limitation is that the good performance of the application in the mountain grasslands of Azerbaijan does not necessarily imply that it will work with equal accuracy in grassland biomes elsewhere. Given this uncertainty, validation will be required and we therefore recommend that implementation of this deductive carrying capacity model in other situations should be accompanied by efforts to validate its aboveground biomass predictions against independent observations from the field.

Another way to control for possible errors is to review the sources of error in the various data and parameters used in the model that leads to ANPP. The precision and accuracy of the aboveground NPP estimate depends on the errors in the MODIS NPP product as well as in the parameter for fraction of NPP allocated to above ground biomass. The remotely sensed GPP and NPP products are processed according to well described procedures that have gone through several stages of internal review and product development (Zhao et al., 2005). An initial review of the performance of the MOD 17 products against GPP estimates by Turner et al. (2008) suggested unbiased overall performance with underestimation at low and very high productivity. A more recent analysis by Schaefer et al. (2012) suggests that MOD17 GPP/NPP tends to overestimate productivity outside the growing season and underestimate during the growing season. This seasonal bias is due primarily to leaf-canopy scaling; MOD17 uses fixed land cover specific terms and does not account for different photosynthetic pathways or other ecophysiological constraints when scaling light use from the leaf to the canopy. Further, MODIS tends to underestimate FPAR, which may influence the negative bias (Yan et al., 2016). For dry grasslands such as in south western Azerbaijan, dry conditions can further enhance this bias because of the moisture constraint used by MOD17, which is derived from humidity estimated with geospatial meteorological data. The formulation may overcompensate for dry conditions during the primary growing season leading to underestimates of GPP, while the meteorological data biases and contributes to overestimation of GPP outside the growing season (Heinsch et al., 2006).

The fraction of NPP allocated to above ground biomass (Hui and Jackson, 2005) has received far less attention, and is probably a parameter with greater uncertainty. The model described by Hui and Jackson (2005) is based on observations from 12 grassland sites globally, which is a small dataset for derivation of a global model and enlargement of this knowledge base appears desirable. The fANPP is normally derived from field based estimates of above and below ground biomass. The collection of below ground biomass estimates is particularly labor-intensive. One way to overcome this limitation would be to build a library of fANPP values by relating satellite-derived estimates of total NPP directly to above ground biomass collected in the field, a procedure that would bypass the necessity to estimate below ground biomass in the field.

The proper use factor in the carrying capacity model accounted for the risk of erosion through the inclusion of slope steepness. Other factors affecting erosion such as for example vegetation ground cover and soil texture were not included in our model. The effect of vegetation ground cover could possibly be brought into the proper use factor while using estimates of leaf area index or the fraction of bare soil from high resolution remote sensing imagery. The availability of global soil maps such as SoilGrids (Hengl et al., 2016) that provide such information would make it possible to include the effect of soil texture or the K factor or soil erodibility which was recently modeled globally from soil texture data in SoilGrids (Borrelli et al., 2017). It is advised to consider including the effects of these erosion controlling factors in future carrying capacity assessments.

The carrying capacity assessment that we present here is based on the average aboveground NPP for a ten-year period. Using ANPP estimates that average multiple years is useful in situations where production does not vary significantly between years, such as in the high-mountain grasslands of Azerbaijan. The advantage of this is that the multi-year average can be used to forecast carrying capacity for years to come and thus use this to advise on appropriate stocking rates. Obviously, this approach does not work well in situations with greater volatility in ANPP; in such situations stocking rates are better adjusted annually according to the prevailing situation.

The use of historic information in GIS based carrying capacity assessments raises the question how robust these assessments will be in view of progressive climate change. One of the possible effects of climate change will be on primary production that is a key input in the model; however any changes NPP will be accounted for by the MODIS NPP product. Similarly we consider that the foreseeable effect of rising temperatures on the fraction of NPP allocated to aboveground production is also already accounted for in our model. Our model does not account for the increase in erosion that will occur with enhanced rainfall intensity that is predicted under progressive climate change and it would be interesting to assess its effects.

When applied to the mountain grasslands of Azerbaijan, our first carrying capacity assessment resulted in an average stocking density of 12.7 sheep per ha. This figure is higher than the average carrying capacity of 5.95 and 8.33 sheep units per ha on south and north facing slopes predicted by Neudert et al. (2013). This difference is because Neudert et al. (2013) used sheep units (1 ewe, 0.04 ram and 0,8 lam) of 90 kg, which have a mass 2.5 times the weight of the average sheep of 36 kg that we used in our model. When using this as a conversion factor, the stocking densities predicted by Neudert et al. (2013) go up to 14.8 and 20.8 sheep per ha, higher than the 12.7 sheep per ha predicted by our model. The difference is understandable, because our prediction holds for the entire territory including the drier pastures in the south while Neudert et al. (2013) focused on the wetter and more productive pastures in the Shahdag area.

The above carrying capacity assessment does not consider a reduction of stocking density on sloping lands. Our second carrying capacity model, which accounted for the need to reduce stocking rates to control for erosion, resulted in a stocking density of 6.2 sheep per ha. These figures concur with the stocking density for the summer pastures prescribed by the Azerbaijani government of 2–8 sheep per hectare.

How do these stocking densities translate to the total number of livestock that can be sustained? A carrying capacity of 6.2 sheep per ha, implies that the 637.200 ha of summer pastures are able host 3.93 million sheep, while the 2–8 sheep per ha prescribed by government results in a carrying capacity of 1.3–5.5 million sheep. These carrying capacity estimates are much lower than the actual number of sheep migrating into the mountains of at least and probably more than 8 million sheep with additional goats and cattle.

Given this we conclude that the mountain pastures of Azerbaijan as a whole are overstocked and overgrazed. Further evidence for overgrazing are our own observations of complete denudation of the mountain pastures at the end of summer as well as reports of stocking rates of 10 to 15 ewes per ha (Guliev, personal communication). This overstocking is possible because there is enough fodder when allowing animals to graze on steep slopes. Obviously, this is undesirable from an environmental perspective, and it is advisable to reduce the current stocking density by one half.

Consequently, the grazing land action plan Azerbaijan (Peeters, 2012) calls for a stricter regulation and implementation of carrying capacity that should be defined geographically explicit per grazing unit. The legislative conditions for implementation of geographically differentiated stocking rates are present since restrictions on grazing intensity can be enforced for the plots that herders lease (Neudert, 2015). The model developed by us provides information on the geographical variation in carrying capacity which can support stakeholders to decide on defining and implementing more sustainable stocking rates.

5. Conclusion

The approach for carrying capacity assessment described here has potential for utilization in grassland areas elsewhere. Overgrazing is a problem worldwide and potentially the approach could be utilized globally. Given its reliance on freely available data the approach is particularly useful for application in areas where data needed for traditional assessment is scarce or difficult to acquire through field sampling. We thus advise to consider using the approach for assessment of carrying capacity of grasslands and rangelands in other parts of the world.

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