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Modeling the impact of rangeland management on forage production of sagebrush species in arid and semi-arid regions of Iran

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ABSTRACT

Rangeland areas in the arid and semi-arid regions of Iran suffer from high grazing pressure and periodic droughts. These regions account for 85% of the national total rangeland area and make an important contribution to country's economy. To determine how to better manage this important resource, we developed a rangeland-livestock model using the Soil and Water Assessment Tool (SWAT). The model was tested in the river basin located in Tehran and Semnan Provinces of Iran. Sagebrush species of *Artemisia sieberi* Besser and *Artemisia aucheri* Boiss (covering more than 38% of the total rangeland areas in Hablehroud river basin) was chosen and some of their characteristics were used to add the necessary plant growth parameters to SWAT landuse database. In combination with the SWAT model, the Sequential Uncertainty Fitting Program (SUFI-2) was used to calibrate and validate the eco-hydrological model of the watershed based on river discharges and forage production of sagebrush species, taking into consideration historic grazing management. The model predicted well rivers discharges at eight hydrometric stations (*P*-factor 0.6–0.9; *R*-factor 0.85–1.5) as well as the sagebrush yield in three ecological zones across the basin. We found that the current grazing intensity was more than twice as much as the region's capacity. Based on some scenario analysis for water and grazing management we showed that through proper water management, we could obtain an average increase of about 40% in sagebrush forage production, while through grazing management an average increase of 30% could be obtained. This shows the region's nutritional capacity could substantially increase. The analytical framework used in this study could be applied to other arid and semi-arid environments for the assessment of forage production and livestock management to achieve a more sustainable food production.

1. Introduction

Rangelands are complex and dynamic ecosystems covering extended areas of the earth and producing many goods and services as direct and indirect products (Alizadeh et al., 2010). Soil, water, plant, climate and animals are the main components of these ecosystems with a complex relation and interactions. A sound knowledge of these factors and their impact on forage production is necessary to analyze the rangeland's social, ecological, and economic sustainability (Vallentine, 2001). Physical and process based models are useful in understanding the complex interactions of the components influencing the sustainability of rangeland ecosystems (CSIRO, 2004).

Different models have been applied in the literature to study processes of rangeland vegetation and forage production. Some examples of the process-based models are: GRASIM (Mohtar et al., 1997, 2000), which is a pasture and grassland model, but it cannot simulate watershed level, water and sediment routing; SPUR (Simulation of Production and Utilization of Rangeland) (Foy et al.,

Abbreviations: BIO_EAT, dry weight of biomass consumed daily (kg ha^{-1} day^{-1}); BIO_MIN, min plant biomass for grazing (kg ha^{-1}); BLAI, maximum potential leaf area index; CN2, SCS runoff curve number; CNOP, SCS run off curve number for moisture condition II; CNYLD, normal fraction of nitrogen in yield (kg N (kg yield)$^{-1}$); DLAI, fraction of growing season when leaf area begins to decline; ESCO, soil evaporation compensation factor; FRGMAX, fraction of maximum stomatal conductance; FRGRW1, fraction of the plant growing season; FRGRW2, fraction of the plant growing season in second point; GSI, maximum stomatal conductance; HEAT_UNITS, total heat units for plant to reach; LAIMX1, fraction of the maximum leaf area index; RCHRG_DP, deep aquifer percolation fraction; REVAPMN, revap coefficient; SFTMP, snowfall temperature (°C); SMFMN, min melt rate for snow (mm °C^{-1} day^{-1}); SOL_AWC, soil available water storage capacity (mm H_2O (mm soil)$^{-1}$); SOL_BD, soil bulk density (g cm^{-3}); SOL_K, soil conductivity (mm h^{-1}); SURLAG, surface runoff lag time (days); T_OPT, optimal temperature for plant growth (°C); WAVP, rate of decline in radiation use efficiency; WSYF, lower limit of harvest index.

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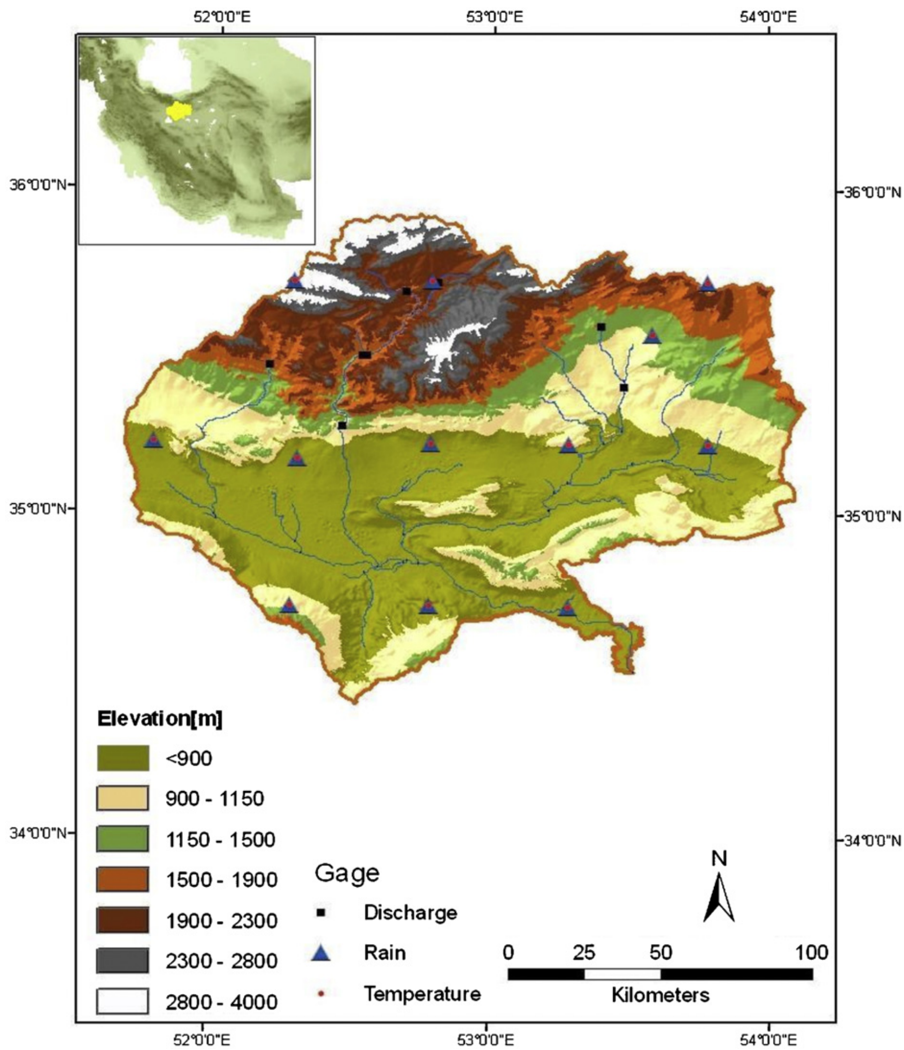

Fig. 1. The Hablehroud river basin with SWAT delineated subbasins, digital elevation model, river network, and meteorological stations.

1999; Corson et al., 2006), which simulates plant growth, water balance, nutrient cycling, and grazing, but it cannot simulate different plant communities (multi-stories) and different growing conditions (Chen, 2000); and GRAZE (Parsch and Loewer, 1995), which is a beef forage grazing model used to estimate animal intake and growth, however, it lacks nutrient and soil components for the study of grazing impact on environment.

Other relevant models are IFSM (Integrated Farm System Model) (Rotz et al., 2012), EPIC (Erosion Productivity Impact Calculator) (Williams, 1995), SVAT (Soil Vegetation Atmosphere Transfer) (Mo et al., 2005), and GEPIC (GIS-based EPIC) (Liu et al., 2007). As mentioned by Faramarzi et al. (2010), a key limitation in many of the process-based models is that the crop yield or forage production and consumptive water use modeled for a given area are not linked with water resources availability of that area. Therefore, one cannot assess directly the aggregated impact of regional water resources availability, landuse, and climate change on crop/forage production. Such models could be used to better understand the impact of grazing on soil, water, and forage production.

Iran with and area of 1,648,195 km^2 has a variety of geographic and climatic conditions, which contribute to its ecological diversity (fauna and flora). Due to its location in earth's arid belt and its specific synoptic conditions, Iran is exposed to the occurrence of drought, an issue emphatically mentioned by the United Nations Convention to Combat Desertification (UNCCD), particularly in the vast central plateau and east and south of the country where the rotation cycle is relatively short (FRWO, 2004). The rangeland areas in arid and semi-arid regions of Iran account for 85% of the national total rangeland area (Badripour, 2006). Despite suffering from heavy grazing and periodic droughts, they make an important contribution to country's economy as well as playing an important role in environmental protection and food security. A long-term policy and strategy for rangeland management is "to establish a comprehensive program for grazing management and rangeland improvement, as part of country's sustainable development program" (Assareh and Akhlaghi, 2009). With this background, developing a model for a systematic assessment of forage production and its sustainable use would be useful.

Artemisia spp. is widespread on Iranian rangelands covering more than 50% of the land cover. Severity of harsh environment in most places and competitiveness of this species does not allow other species to maneuver. Hence, calculating their production would be equivalent to calculating the main forage production of the rangelands in the country. These lands are often associated with grazing of livestock (e.g. sheep, goat) and wildlife in arid and semi-arid regions of the country (Mozafarian, 1997; Mirhaji, 2000). In this research we used the program Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) to predict rangeland forage production and to establish a basis to test water and grazing management options in Hablehroud river basin. SWAT was chosen because it

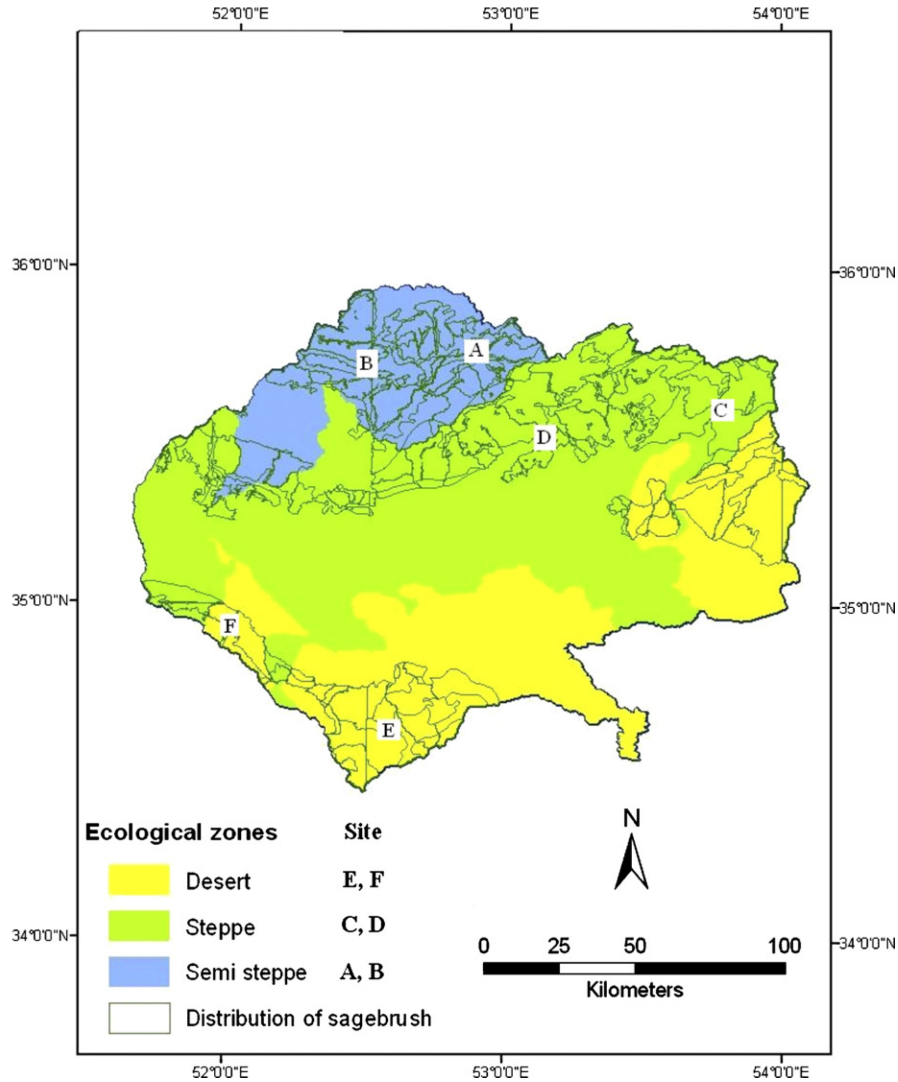

Fig. 2. Distribution of sagebrush and ecological zones based on the long term mean annual rainfalls. Also shown are the six ecological sites selected to study *Artemisia* spp.

couples hydrology, plant growth, nutrient cycling, soil erosion, and climate. It is also widely used to simulate the ecological, hydrological, and environmental processes under a range of climatic and management conditions throughout the world (Gassman et al., 2007).

The main objectives of this study are (i) to model forage production and leaf area index (LAI) of dominant sagebrush species, (ii) to calibrate from 2007 to 2011 and to validate from 2003 to 2004 the model for forage production, and (iii) to use the calibrated model for the assessment of current and future range management scenarios.

2. Materials and methods

2.1. Description of the study area

Hablehroud river basin is located between 51°40′ to 53°05′ east and 34°25′ to 36° north covering most of the Tehran and Semanan provinces in northern Iran (Fig. 1). Hablehroud river basin originates from Alborz Mountain in the north and continues to Garmsar plain approximately in central part of Iran. Diversity of climate, soil, and slope causes different vegetations to adapt to the specific ecological conditions in the area. *A. si* and *A. au* were modeled because they occupy more than 50% of the total rangelands in Iran and more than 38% in Hablehroud river basin (RIFR, 2008). *Artemisia* spp. in Iran, like other parts of the world, has a wide distribution and can be seen in most regions of the country (Zohary, 1963). It is a perennial plant and its stages of plant life include growth initiation, flowering, dissemination, and dormancy. Hablehroud river basin has been selected as a pilot area in regional research and also by the United Nations Global Development Network (UNDP) for studying sustainable management (FRWO, 2005).

Using 30 years of weather data from synoptic weather stations and based on the long-term mean annual rainfalls (Badripour, 2006); we selected three ecological zones to study: the semi-steppe, steppe, and desert as the climate shifts from semiarid to arid condition. In each zone we then established two sites for studying *Artemisia* spp. (Fig. 2).

The climate of Hablehroud river basin is continental, with average minimum temperature of −10.7 °C in the semi-steppe, and average maximum temperature of 40.1 °C in the desert. Variations in elevation are very large throughout the basin ranging from 725 to 4000 m above the sea level. Mean annual precipitation is around 280 mm in the north and around 100 mm in the south of the watershed (Table 1).

All three ecological zones are dominated by *Artemisia* spp. Grazing with domestic livestock (mainly sheep and goat) is the major landuse of Iranian rangelands. The studied areas have been grazed by domestic livestock under a transhumance or

Table 1
Site characteristics of the semi-steppe, steppe and desert ecological zones in Hablehroud river basin (FRWO, 2005).

	Semi-steppe	Steppe	Desert
Mean annual precipitation (mm)	281	158	100
Maximum temperature (°C)	28.2	37.3	40.1
Minimum temperature (°C)	−10.7	0	2
Soil orders	Inceptisols-Entisols	Entisols–Aridisols	Aridisols
Soil moisture regime	Xeric	Aridic	Aridic or Torric
Soil thermal regime	Frigid-Mesic	Mesic–Thermic	Thermic
Dominant sagebrush species	*A. au*	*A. si*	*A. si*
Typical dry forage production of sagebrush rangeland ($t\,ha^{-1}$)	0.330–0.450	0.150–0.250	0.050–0.110
Grazing capacity (AUM[a]/ha)	6–8	4–6	2–4

[a] Animal unit month.

semi-transhumance regime for thousands of years (FRWO, 2005). Although grazing practices vary somewhat depending on local geography, the basic pattern of seasonal use is similar in all three zones; annual migrations take place from mountainous cold rangelands toward the warmer plains in the beginning of autumn, with the reverse movement in the spring when temperature increases. Sheep and goat are the most common livestock in Hablehroud river basin and their population is about 1.5–2.5 times more than the capacity of forage production (FRWO, 2005). Therefore, heavy and untimely grazing, and lack of proper management principles are the important issues to be investigated in this basin.

2.2. Field data collection

To determine the parameters of *Artemisia sieberi* and *Artemisia aucheri* for inclusion in the SWAT landuse database, we used measured and historical data. Historical data were obtained for annual forage production and area covered with rangelands from 2003 to 2004 period from Iranian Forests, Rangeland and Watershed Organization (FRWO), and from 2007 to 2008 period from Iranian Research Institute of Forest and Rangelands (RIFR). Grazing and related management data (e.g. date of grazing, type and number of animals grazed) were obtained from FRWO. Field data were collected from 2009 to 2011, where next to LAI and forage production, we also measured the distribution of *Artemisia* spp. in two selected sites in each ecological zone (Fig. 2). For the sake of uniformity six transects were placed on each site. The first transect was installed randomly while others were set systemically with 10-km intervals. Alongside each transect, 10 species were selected for defoliation. Due to the size of the species, canopy, and the smallness of the leaves, leaves were taken from a quarter of each plant. The relationship between weight and leaf area was used to calculate LAI, which was measured at different phenological stages of *Artemisia* spp. Leaf area was measured using a flatbed scanner (light AOX 230V, GATEHOUSE, U.K.) and processed by computer. Leaves were kept at 4 °C until they were measured in the lab. Then leaves were oven-dried for 48 h at 70 °C in the laboratory to measure the weight. Forage production (the weight of forage that is produced within a designated period of time) on a given area, was measured using a double-sampling method suggested by Arzani and King (1994).

2.3. Model description

SWAT is a comprehensive, physically based model that was developed to predict the impact of land management practices on water, sediment and forage production in large complex watersheds with varying soils, landuse, and management conditions over long periods of time. It requires specific information about water, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, plant growth,

Table 2
The most influential SWAT parameters for discharge and LAI.

Ecological zone	Parameter name	Initial parameter range	Final parameter range	*t*-Value[b]	*p*-Value[c]
Semi-steppe	v_SFTMP.bsn[a]	0 to 5	2.38 to 2.98	10.74	0
	v_DLAI.CROP	0.25 to 0.55	0.3 to 0.32	8.53	6.36×10^{-8}
	v_SMFMN.bsn	0 to 5	0.8 to 1.5	6.68	5.6×10^{-7}
	v_SURLAG.bsn	1 to 12	5.25 to 6.5	4.38	3.75×10^{-7}
	r_SOL_BD.sol	−0.5 to 0.5	−0.27to −0.14	5.30	8×10^{-4}
	r_CN2.mgt	−0.5 to 0.5	−0.32 to −0.19	4.11	3×10^{-3}
Steppe	v_HEAT_UNITS.mgt	500 to 2500	1000 to 1100	11.8	8.56×10^{-10}
	v_BLAI.CROP	0.05 to 4	1.5 to 2.5	9.17	7.3×10^{-6}
	r_CN2.mgt	−0.5 to 0.5	−0.26 to −0.15	8.68	4×10^{-6}
	r_SOL_BD.sol	−0.5 to 0.5	−0.22 to −0.12	9.3	8.2×10^{-5}
	v_GSI.CROP	0.004 to 0.006	0.004	7.1	3.5×10^{-5}
	r_SOL_AWC.sol	−0.5 to 0.5	−0.21 to −0.16	6.4	2×10^{-4}
	v_FRGRW1.CROP	0.04 to 0.06	0.043 to 0.046	7.6	3.7×10^{-5}
	v_REVAPMN.gw	350 to 400	355.6 to 387.3	7.3	2.7×10^{-3}
Desert	v_GSI.CROP	0.004 to 0.006	0.0041 to 0.0043	9.36	0
	v_ESCO.hru	0.01 to 1	0.65 to 0.75	10.1	5.2×10^{-7}
	r_SOL_K.sol	−0.5 to 0.5	0.05 to 0.2	9.8	6.4×10^{-6}
	r_SOL_AWC.sol	−0.5 to 0.5	−0.3 to −0.1	9.36	5.8×10^{-6}
	v_LAIMX1.CROP	0.05 to 0.2	0.11 to 0.2	8.4	5.1×10^{-6}
	r_CN2.mgt	−0.5 to 0.5	−0.4 to −0.1	10.1	6.7×10^{-5}
	v_RCHRG_DP.gw	0 to 1	0.5 to 0.8	10.5	8×10^{-4}
	v_BLAI.CROP	0.05 to 4	0.7 to 1.9	8.2	2.2×10^{-4}
	v_FRGRW2.CROP	0.15 to 0.35	0.1 to 0.2	7.4	7.7×10^{-3}
	r_SOL_BD.sol	−0.5 to 0.5	−0.3 to −0.1	6.3	5.2×10^{-3}
	v_T_OPT.CROP	15 to 35	19 to 21.5	5	3.5×10^{-3}

Table 3
The most influential SWAT parameters to forage production.

Ecological zone	Parameter name	Initial parameter range	Final parameter range	*t*-Value[b]	*p*-Value[c]
Semi-steppe	v_T_OPT.CROP[a]	15to 35	20.2to 20.6	11.37	9.64×10^{-10}
	v_FRGMAX.CROP	0.65 to 0.8	0.75 to 0.78	8.32	2×10^{-8}
	v_WSYF.CROP	0.8 to 1.1	0.8 to 0.83	6.59	6×10^{-8}
	r_CNOP.mgt	−0.5 to 0.5	−0.26 to −0.24	4.15	4.3×10^{-7}
	r_CNYLD.CROP	−0.5 to 0.5	0.35 to 0.46	6.50	3.75×10^{-5}
Steppe	v_LAIMX1.CROP	0.05 to 0.2	0.13 to 0.15	6.8	2.36×10^{-7}
	r_SOL_AWC.sol	−0.5 to 0.5	−0.21 to −0.16	3.97	9.1×10^{-6}
	r__SOL_BD.sol	−0.5 to 0.5	−0.22 to −0.12	2.93	7.2×10^{-5}
	v_BIO_EAT.mgt	0 to 10	1.9 to 2.3	2.87	5.5×10^{-5}
	v_WAVP.CROP	9 to 11	9.17 to 9.6	2.54	5.5×10^{-4}
	v_T_OPT.CROP	15 to 35	19 to 20.6	2.48	7.3×10^{-4}
	r_CNOP.mgt	−0.5 to 0.5	−0.14 to 0.02	2.37	3.7×10^{-4}
	v_BIO_MIN.mgt	50 to 150	74 to 82	3.3	2.7×10^{-3}
	v_FRGRW1.CROP	0.04 to 0.06	0.043 to 0.046	2.36	2.1×10^{-3}
Desert	v_BLAI.CROP	0.05 to 4	0.7 to 1.9	15.1	2.5×10^{-17}
	r_CN2.mgt	−0.5 to 0.5	−0.4 to 0.1	14.8	2.3×10^{-15}
	r_SOL_AWC.sol	−0.5 to 0.5	−0.3 to −0.1	10.4	2.1×10^{-12}
	r_SOL_BD.sol	−0.5 to 0.5	−0.3 to −0.1	10.9	6.7×10^{-10}
	v_BIO_MIN.mgt	50 to 150	35 to 40	11.5	8×10^{-8}
	v_RCHRG_DP.gw	0 to 1	0.5 to 0.8	10.2	2.2×10^{-8}
	v_LAIMX1.CROP	0.05 to 0.2	0.11 to 0.2	12.4	7.7×10^{-7}
	v_FRGRW2.CROP	0.15 to 0.35	0.1 to 0.2	5.6	3.5×10^{-4}
	v_CNYLD.CROP	0.015 to 0.03	0.03	3.2	3.5×10^{-4}

[a] v: parameter value is substituted by a value from the given range; r: parameter value is multiplied by (1 + a given value) (Abbaspour et al., 2007).
[b] *t*-Value shows a measure of sensitivity: the larger *t*-value are more sensitive.
[c] *p*-Value shows the significance of the sensitivity: the smaller the *p*-value, the less chance of a parameter being by chance assigned as sensitive.

nutrient cycle, etc. are directly modeled by SWAT using these input data (Neitsch et al., 2011).

The plant growth component of SWAT is a simplified version of the EPIC plant growth model. Differences in growth between plant species are defined by the parameters contained in the land-use database. Plant growth is simulated by computing leaf area development, light interception and its conversion to biomass and forage production (Neitsch et al., 2011). LAI and root development are simulated using the plant growth component of SWAT. Phenological plant development is based on daily accumulated heat units, potential biomass, and harvest index. Harvest index is the fraction of above-ground dry biomass that is removed as dry economic forage production. Plant growth in the model can be inhibited by temperature, water, nitrogen, and phosphorus stress factors.

Plant communities that have been simulated using SWAT include: crops and weeds, trees and grasses, different tree species in a boreal forest, and grasses and shrubs in rangeland communities. Management operations that control the plant growth cycle such as beginning of growing season, harvest, end of growing season, tillage, grazing, fertilizer, irrigation, and pesticide are included in the SWAT (Neitsch et al., 2011).

2.4. Model input and parameterization

Data required for this study were compiled from different sources. They included: Digital Elevation Model (DEM) extracted from the Global NASA/NGA 90 m Shuttle Radar Topography Mission (SRTM) dataset; landuse and soil maps from the FRWO with spatial resolution of 50 m and FAO (1995), and weather input data (daily precipitation, maximum and minimum temperature, daily solar radiation), which were obtained from Public Weather Service of the Iranian Meteorological Organization (WSIMO) for 3 synoptic stations. Weather data from another 10 stations were obtained from the Climatic Research Unit (CRU) (Mitchell et al., 2004) (Fig. 1). Periods covered by the available data were from 1982 to 2011 with 3 years of initialization.

The method of Hargreaves (1985) was used to calculate evapotranspiration. The hydrologic model was first calibrated using data from 1996 to 2009 and validated from 1985 to 1995. The forage production model was then calibrated using data from 2007 to 2011 and validated from 2003 to 2004. Average temperature and precipitation were similar in these two periods.

2.5. Calibration setup and analysis

We used 8 hydrometric stations to calibrate and validate the hydrological model. Based on literature, 22 discharge parameters (Faramarzi et al., 2009; Abbaspour et al., 2007; Wang et al., 2005), 23 parameters related to plant growth (Wang et al., 2005; Corson et al., 2006; Luo et al., 2008; Faramarzi et al., 2010) and another 8 parameters related to grazing (Mohtar et al., 1997; Corson et al., 2006; El-Awar et al., 2007) were initially selected for optimization.

For calibration and uncertainty analysis in this study, we used the Sequential Uncertainty Fitting Program SUFI-2 (Abbaspour et al., 2007; Abbaspour, 2011). In this algorithm all uncertainties (parameter, conceptual model, input, etc.) are mapped on the parameter ranges as the procedure tries to capture most of the measured data within the 95% band of prediction uncertainty. The overall uncertainty in the output is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling. Two indices are used to quantify the goodness of calibration/uncertainty performance

Table 4
Calibration and validation results at the eight hydrometric stations.

Hydrometric station	Calibration (1996–2009)		Validation (1985–1995)	
	P-factor	*R*-factor	*P*-factor	*R*-factor
Firozkoh	0.72	1.4	0.7	1.1
Namrud	0.75	1.45	0.84	0.79
Darjezin	0.7	0.9	0.82	1.11
Delichay	0.65	1.28	0.71	1.23
Simindasht	0.9	1.04	0.71	1.03
Kilan	0.6	1.5	0.59	0.83
Hajiabad	0.75	1.07	0.96	1.14
Bonkoh	0.73	0.81	0.85	0.65

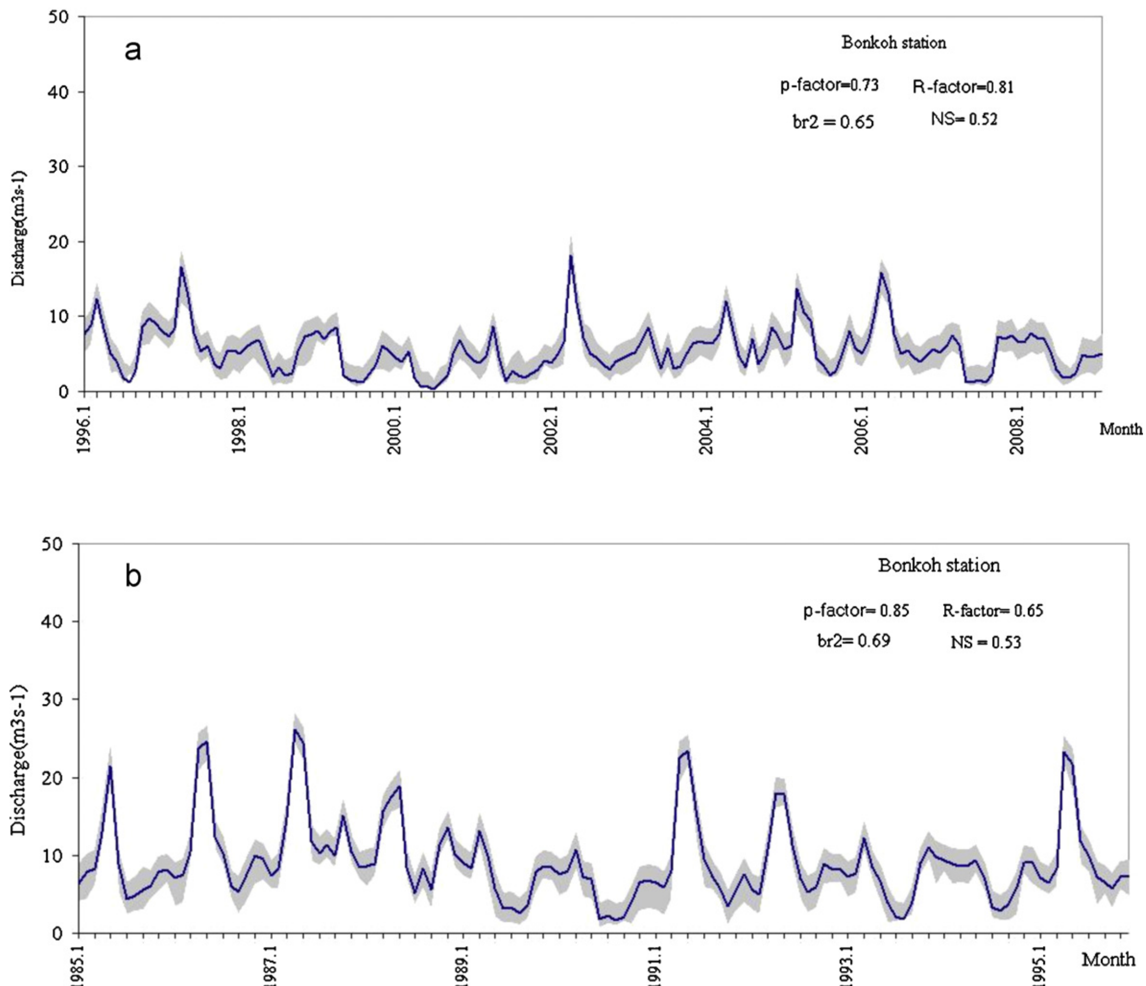

Fig. 3. Comparison of the observed (solid line) and simulated (expressed as 95% prediction uncertainty band) discharges for Bonkoh station. Calibration (a) and validation (b) results are shown.

(Abbaspour et al., 2004, 2007), the *P*-factor, which is the percentage of data bracketed by 95PPU band (maximum value 100%), and the *R*-factor, which is the average width of the band divided by the standard deviation of the corresponding measured variable. Ideally, we would like to bracket most of the measured data (plus their uncertainties) within the 95PPU band (*P*-factor → 1) while having the narrowest band amplitude (*R*-factor → 0).

In order to compare the measured and predicted monthly discharges as well as the LAI we used the following criterion modified from Krause et al. (2005):

$$\phi = \begin{cases} bR^2 & \text{for } 0 < b \le 1 \\ b^{-1}R^2 & \text{for } b > 1 \end{cases}, \tag{1}$$

where R^2 is the coefficient of determination and b is the slope of the regression line between the measured and predicted signals. The objective function containing multiple discharge stations and LAI's measured at different sites was formulated as:

$$g = \frac{1}{2}\left[w_1 \frac{1}{n_1}\sum_{i=1}^{n_1}\phi_i + w_2 \frac{1}{n_2}\sum_{j=1}^{n_2}\phi_j\right], \tag{2}$$

where n_1 is the number of discharge stations, n_2 is the number of sites with LAI measurements, and w_1 and w_2 are the weights associated with each variable, which were set to 1 in this case. The function ϕ varies between 0 and 1. In this form, the objective function, unlike for example Nash-Sutcliffe, which may range from $-\infty$ to 1, is not dominated by any one or a few badly simulated stations (Abbaspour et al., 2009). For forage, which was calibrated after calibrating the model for discharge and LAI, we used MSE (mean square errors) as the objective function (Abbaspour et al., 2009):

$$g = \frac{1}{n_2}\sum_{i=1}^{n_2}(Y_i^o - Y_i^s)^2, \tag{3}$$

where n_2 is the number of sites with forage production data, Y^o (t ha^{-1}) is the observed forage production, and Y^s (t ha^{-1}) is the predicted forage production.

2.6. Calculation of the sustainable grazing capacity

To determine the sustainable grazing capacity, we used the model of Holechek et al., 2004 expressed as:

$$\text{AUD} = \frac{\text{Available forage}}{\text{Animal demand}} = \frac{\text{Forage production} \times \text{Proper use factor} \times \text{Area}}{\text{Animal demand}}, \tag{4}$$

$$\text{AUM} = \frac{\text{AUD}}{30}, \tag{5}$$

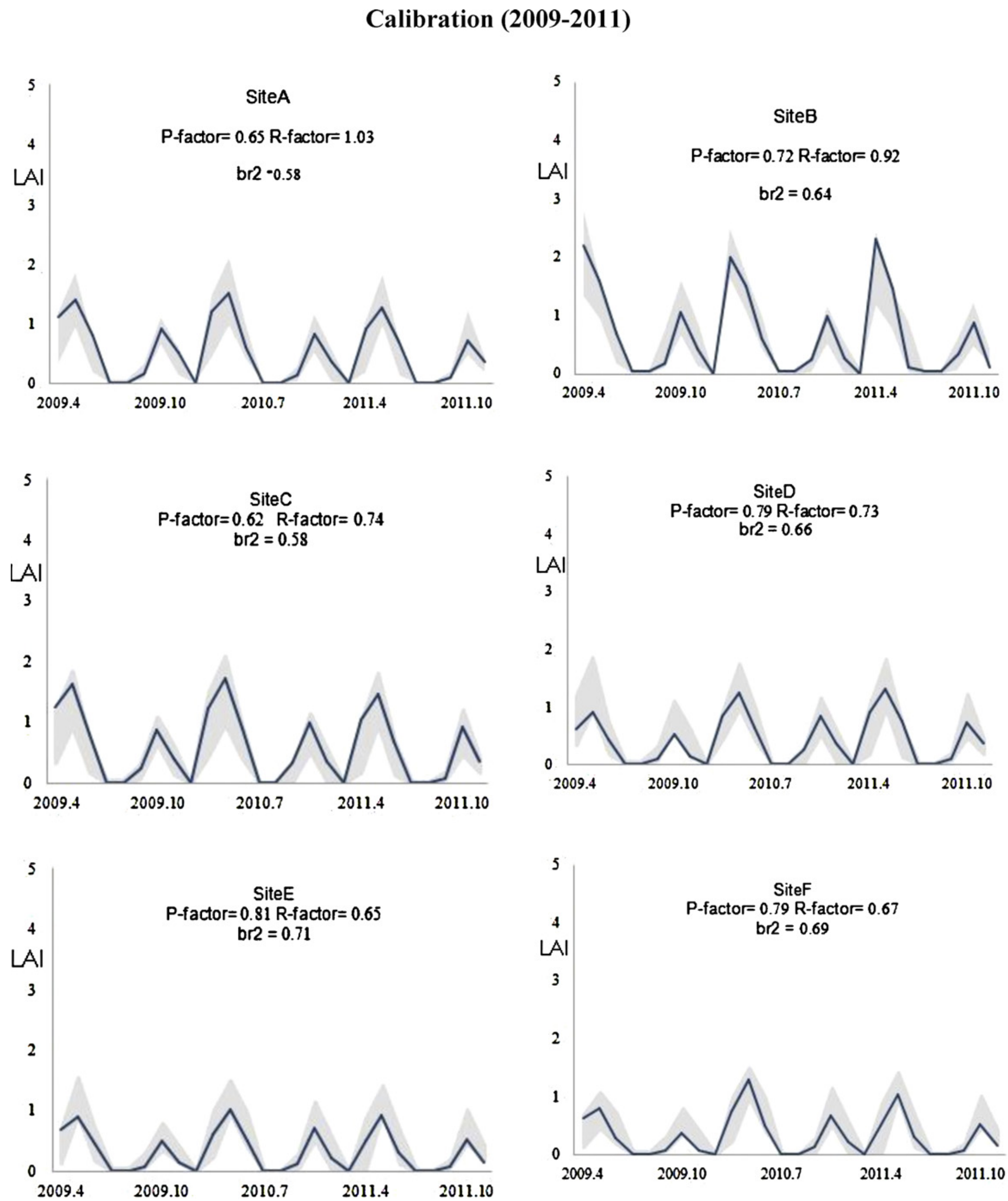

Fig. 4. Calibration results of LAI for sites A and B (semi-steppe), C and D (steppe), and E and F (desert). Solid line is the observation and simulated results are expressed as 95% prediction uncertainty band.

where “Forage production” is the dry weight of forage ($t\,ha^{-1}$), “Proper use factor” is the allowable use defined as the proportion of forage production that can be grazed without hurting the plant life, “Animal demand” is the dry weight of forage that provides the necessary energy for living animals in a day (1.5–1.7 kg), AUD is the animal unit per day, and AUM is the animal unit per month or the monthly grazing capacity. To calculating sustainable grazing capacity, we used the predicted forage production ($t\,ha^{-1}$) and grazing parameters of the SWAT calibrated model such as BIO_EAT (Dry weight of biomass consumed daily, $t\,ha^{-1}\,day^{-1}$) and BIO_MIN (minimum forage production for grazing, $t\,ha^{-1}$).

Grazing begins in both steppe and desert in the flowering time of the plant around September 15 and lasts for 120 days. But due to the lack of management and control, grazing can often begin earlier not allowing the plant to complete its phenological cycle; hence, decreasing seed production, which will set off a vicious circle of poor production. Implementation of suitable policies is necessary to ensure a healthy interaction between grazing and sustainable sagebrush growth. In the following, using the calibrated echo-hydrological SWAT model, we predict the impact of different management scenarios.

2.7. Assessing some rangeland management policies

Based on a strategic framework for developing and promoting natural resources research (Assareh and Akhlaghi, 2009), the objectives of rangeland management programs include: balancing the livestock grazing for sustainable management, providing range management scenarios to control regions in danger of desertification, and implementing policies to increase forage production through efficient use of land and water resources. Management of the number of animals that can be sustained without irreversible damage to the soil and vegetation resources is a serious challenge. Two management scenarios were investigated. First, the impact of water management was simulated through application of irrigation. In practice this is usually implemented by rainwater harvesting through check dams and terracing. In the second scenario we investigated protection of the region from continuous

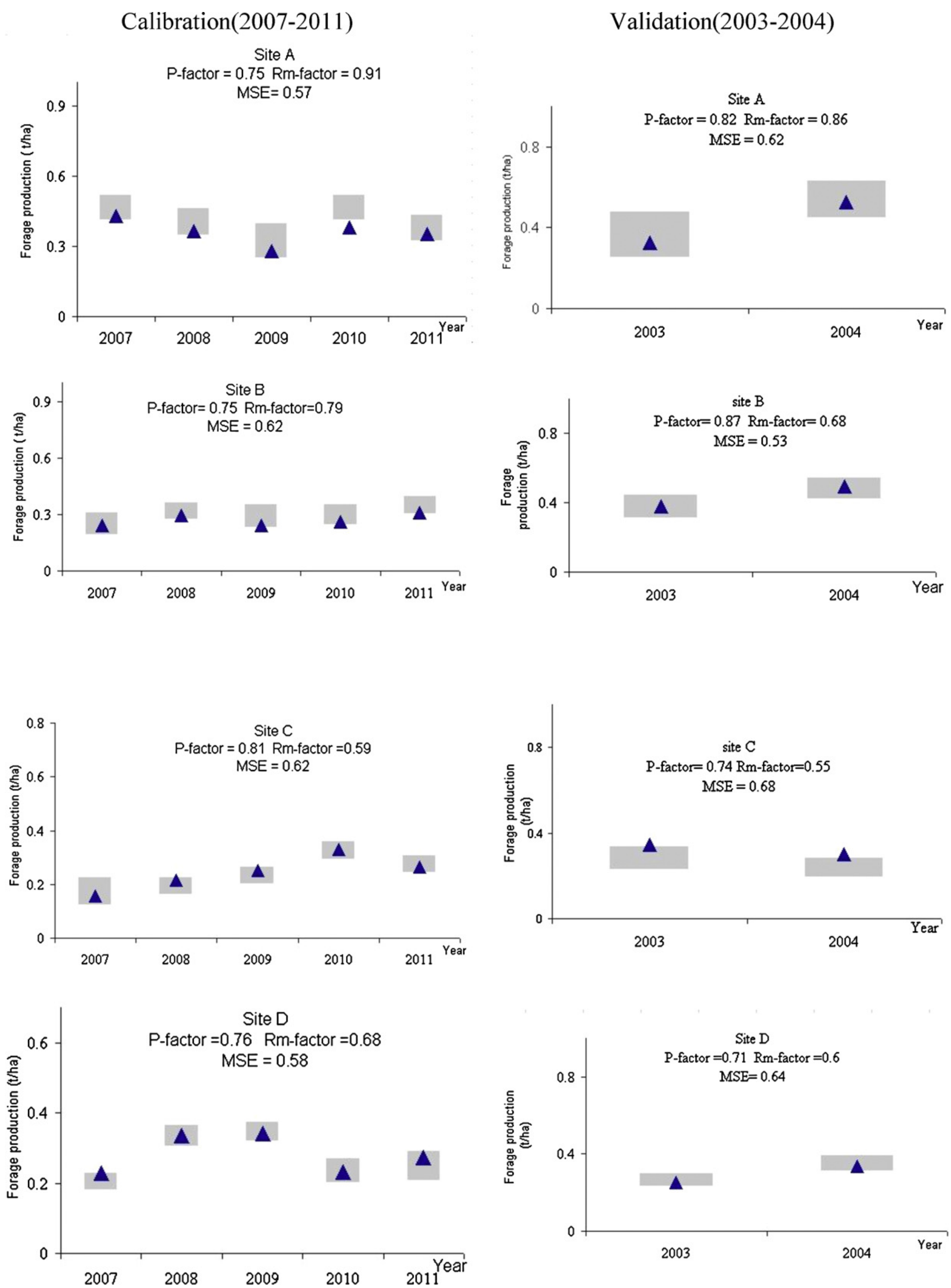

Fig. 5. Calibration and validation results of forage production for six selected sites in three ecological zones. Symbols are observed values and simulated results are expressed as 95% prediction uncertainty band.

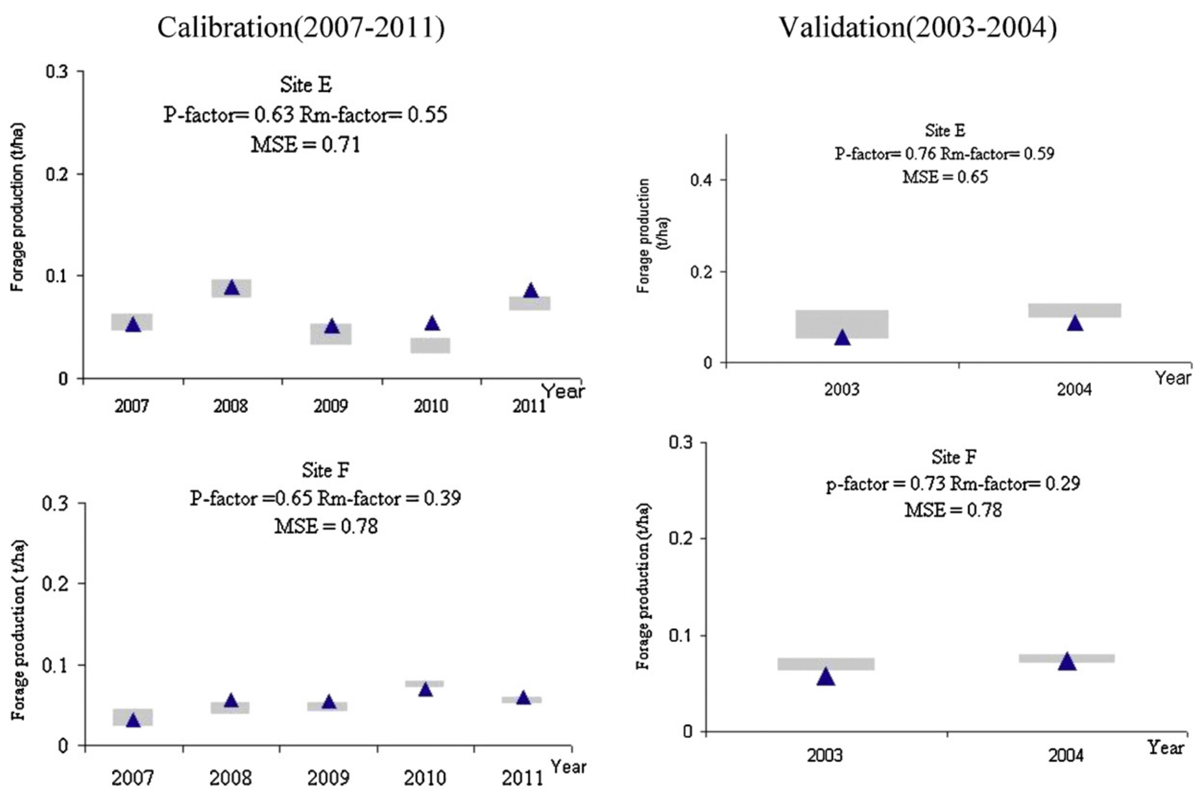

Fig. 5. (*Continued*).

grazing by allowing grazing to take place every other year. As a reference scenario we consider no grazing with water availability for *Artemisia* spp. at the level of long-term mean of precipitation.

2.8. Critical Continuous Day Calculator

We used a program called Critical Continuous Day Calculator (CCDC) (downloadable from www.swatcupiran.com) to calculate the number of continuous days in which precipitation, soil moisture, and maximum temperature meet certain constraints with respect to the number of days and given critical values. For example, a dry period is calculated by counting the number of days where maximum temperature is above 30 °C, precipitation is <2 mm day^{-1}, and soil moisture is <0.2 mm mm^{-1}. If the number of days is above 120, then this is considered a dry event. CCDC uses SWAT's (output.hru) and SWATCUP's (95ppu.txt) output files as inputs to run.

3. Results and discussion

3.1. Model results

For the objective function in Eq. (2), the most influential parameters for different climatic regions are given in Table 2. Also reported in the table are initial and final parameter ranges, were final ranges are the calibrated parameter ranges. In general, as we move from semi-steppe to desert, the number of influential parameters increase and the soil parameters become more influential. It appears that when rainfall is scarce soil parameters play a more important role in water management. CN2, which is usually the most influential hydrological parameter being responsible for partitioning the rainfall into runoff and infiltration plays a secondary role here. This could be due to a relatively low rainfall rate in the watershed. Next to the soil parameters, the maximum stomatal conductance GSI is the most important parameter in the desert zone. GSI controls the water loss from the soil through the plants. Dry climates can influence photosynthesis either through pathway regulation by stomatal closure and decreasing the flow of CO_2 into leaves (Chaves et al., 2003; Flexas et al., 2004), or by plant physiological responses to stresses such as high radiation and low vapor pressure deficit causing smaller values of GSI to control photosynthesis to decrease evapotranspiration. Another influential parameter in the desert is the soil evaporation compensation factor ESCO. For most climatic regions the value of ESCO is around 0.8–1.0. However, in the desert this value could be much lower in order to meet the evaporative demand from the deeper soil layers.

Notice that in the semi-steppe region snowfall parameters (SFTMP, SMFMN) are among the most influential parameters. The hydrology in this region is mostly governed by the snowfall and snow melt processes. The semi-steppe region contains the famous Damavand Mountain with a height of 5600 m, which is the main source of water throughout the year.

In Table 3, as we move from semi-steppe to desert the temperature parameter for plant growth T_OPT becomes less and less important and is not among the influential parameters in the desert. Management parameters, in general, become more influential in steppe and desert regions.

Calibration statistics for the Bonkoh discharge station (Table 4) indicates bracketing of more than 60% (*P*-factor ranges from 0.6 to 0.9) of the observed data within the 95PPU band (Fig. 3). The *R*-factor ranges from 0.85 to 1.5. The overall calibration results are quite satisfactory although at Kilan, Namrood, and Firoozkoh in the semi-steppe zone the uncertainty is larger than the other stations. This could be due to the high level of water and land management as well as other water sources such as springs, which were not accounted for in the model due to lack of data. The validation results have in general smaller prediction uncertainties as indicated by smaller *R*-factors. This could be due to fewer years of data allocated to validation. Although the calibration period covers a period of 14 years, quite few data points existed in some stations.

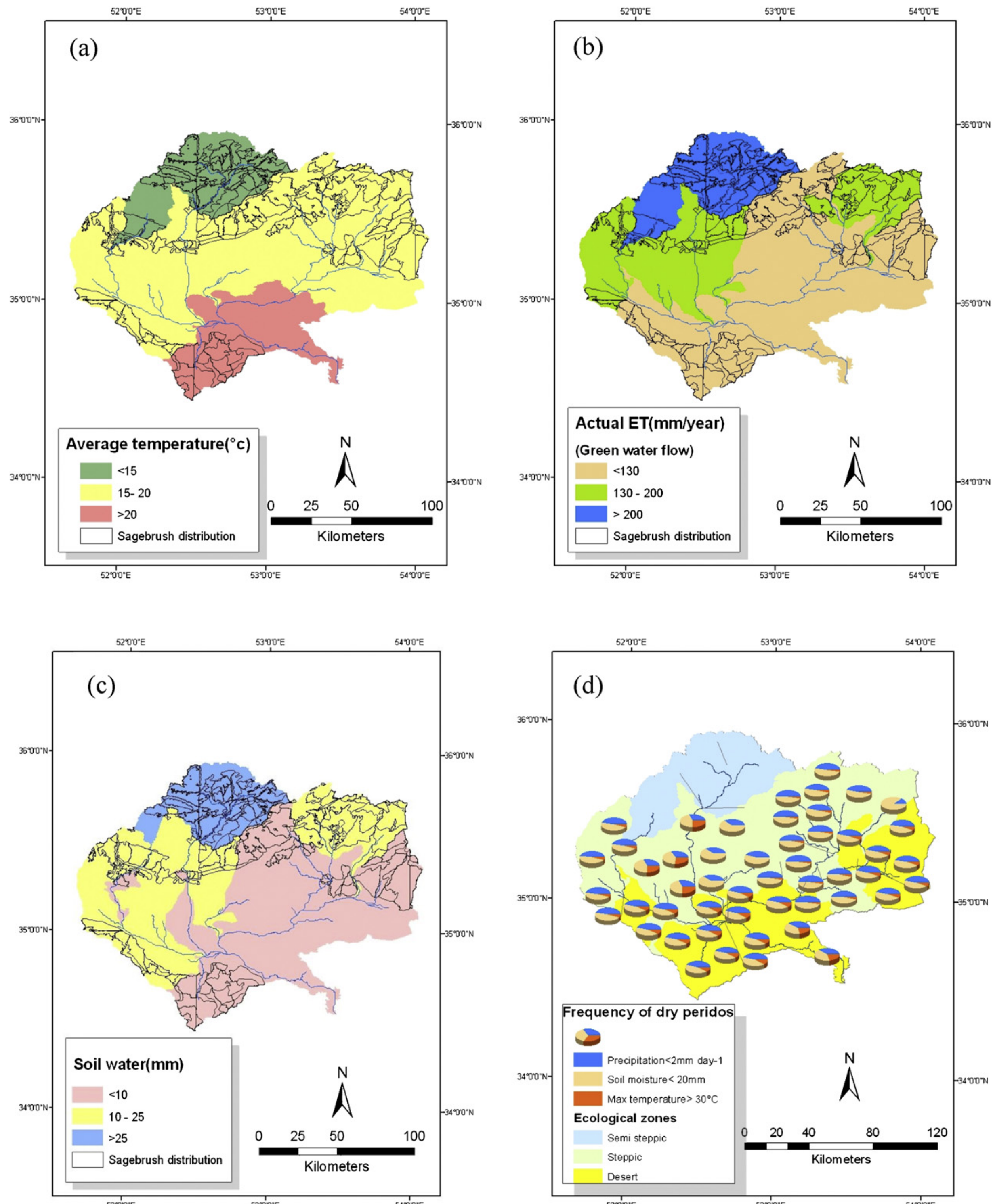

Fig. 6. Distribution of the average temperature (1985–2011) (a), actual evapotranspiration (ET) (b), soil water (c), and the frequency of dry periods (d).

Most of the observed LAI are bracketed in the 95PPU in the three ecological zones and the *R*-factor is relatively small indicating small prediction uncertainties (Fig. 4). In warmer ecological zones LAI is generally smaller. The calibration results show that the model predicts this phenomenon well and is influential to the changes in temperature in different ecological zones.

Observed forage productions are inside or quite close to the predicted bands in all three zones (Fig. 5). Based on the model results, in semi-steppe the forage production varies from 0.35 to 0.5 t ha^{-1}, in steppe from 0.15 to 0.26 t ha^{-1}, and in desert from 0.033 to 0.1 t ha^{-1}. These values are quite close to the observations reported in Table 1.

Similar to discharge, the forage production in the semi-steppe region contains larger uncertainties (Fig. 5). As discussed before, this is a zone of high water management and varying agricultural practices. Some of these practices such as check dams and water

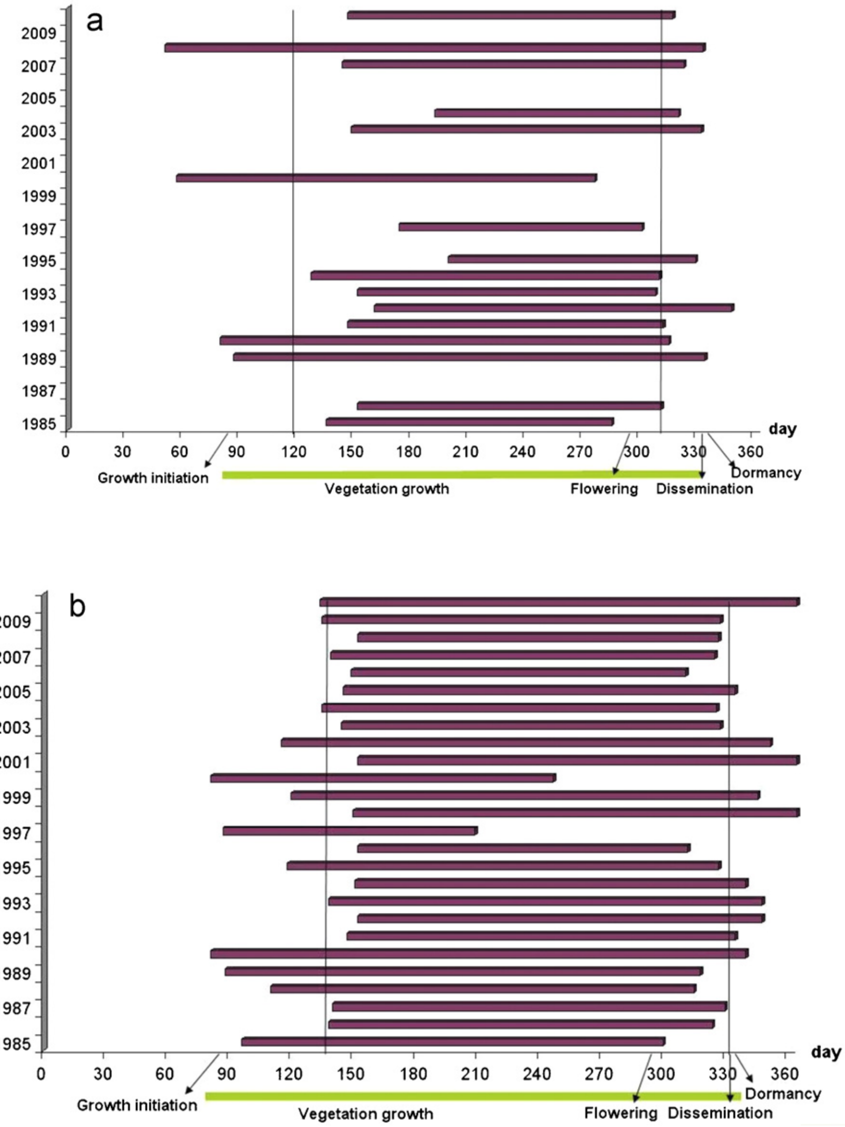

Fig. 7. The phenological period of sagebrush and duration of dry-periods for precipitation in steppe (a) and desert (b) zones.

harvesting could not be accounted for in the model, hence causing larger uncertainties in the prediction.

For a general overview of the hydrology in the three ecological zones, we plotted the temperature, actual ET, soil water, and the frequency of dry periods, respectively, in Fig. 6a–d. These maps were calculated at the 50% probability level of the prediction uncertainty. There is a pronounced variation in these variables across the ecological zones. Precipitation decreases substantially from semi-steppe to desert with a significant increase in the average temperature (Fig. 6a). This causes large changes in both actual ET (Fig. 6b) and the soil water (Fig. 6c). As forage production and ET are directly proportional, calibration of the model based on forage production as well as discharge increases our confidence on ET and consequently soil moisture. In the semi-steppe zone, soil moisture and actual ET are larger than the others because of higher precipitation.

To highlight the forage production and grazing management of the ecological zone, we plotted frequency of dry periods for precipitation in Fig. 6d and distribution of onset, duration, and ending of the dry periods in Fig. 7a and b for a typical area in the steppe zone and in the desert, respectively. No precipitation-dry-periods were observed in the semi-steppe zone during the simulation period of 1985 to 2011. Fig. 6d shows that in the steppe zone soil moisture and precipitation-dry-periods are observed quite frequently, while temperature-dry-periods do not occur often. In the desert, however, all three dry-periods (i.e., for temperature, precipitation, and soil water) occur frequently. In Fig. 7a and b, the phenological period of sagebrush is also illustrated. In general, the onset and duration of dry-periods for precipitation is more frequent and longer in the desert than in the steppe. It is clear from the figure that during vegetative and flowering stages, the sagebrush in the desert experiences drier climate, hence the forage production in the desert is smaller due to higher water stress (Table 1).

The current forage production and the sustainable grazing capacity are shown in Figs. 8a and 9a, as calculated by Eq. (3). The actual grazing capacity reported by FRWO (2005), however, is twice as much as what has been calculated here. Overgrazing causes reduction in cover, long-term change in species composition, and a change in productivity. FRWO (2005) reported that such changes were already taking place in our study regions. As a result, some rangelands are plowed and put under crop production such as wheat, corn, or orchards. As crops generally have shallower rooting depths, these changes in the landuse may cause severe soil erosion.

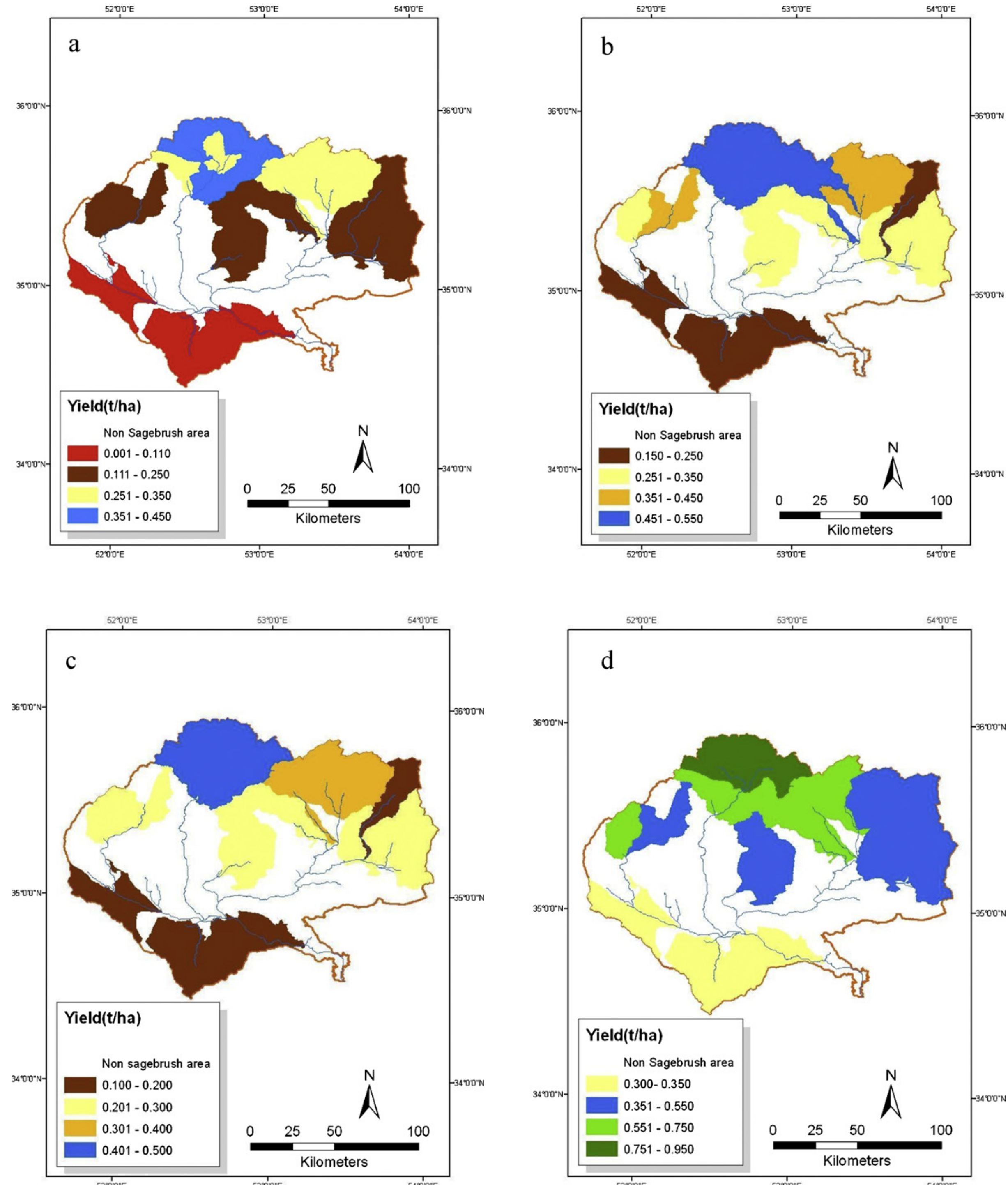

Fig. 8. Forage production maps; the current forage production (a), forage production with the impact of water management (b), forage production with the impact of grazing management (c) and potential forage production (d).

Also because of irrigation and soil salinization, downstream water quality degradation will ensue.

The spatial distribution of forage production, *Artemisia* spp. is shown when the auto irrigation option of SWAT was applied (Fig. 8b). The effect of this option is that it adds water to the soil whenever the plant experiences water stress but not more than the long-term annual average. The model predictions showed a 40% increase in the forage production of sagebrush in the desert, 45% in the steppe, and 30% in semi-steppe regions. The model predictions also showed a 49%, 56% and 42% increase grazing capacity in the desert, steppe and semi-steppe, respectively (Fig. 9b).

Under the impact of the grazing management on forage production and grazing capacity scenario we could expect a forage production increase of 33% in the desert, 35% in the steppe, and 26% in the semi-steppe region (Figs. 8c and 9c). Results showed that on the average, the potential forage production of the region is more than twice as much as the current production (Fig. 8d).

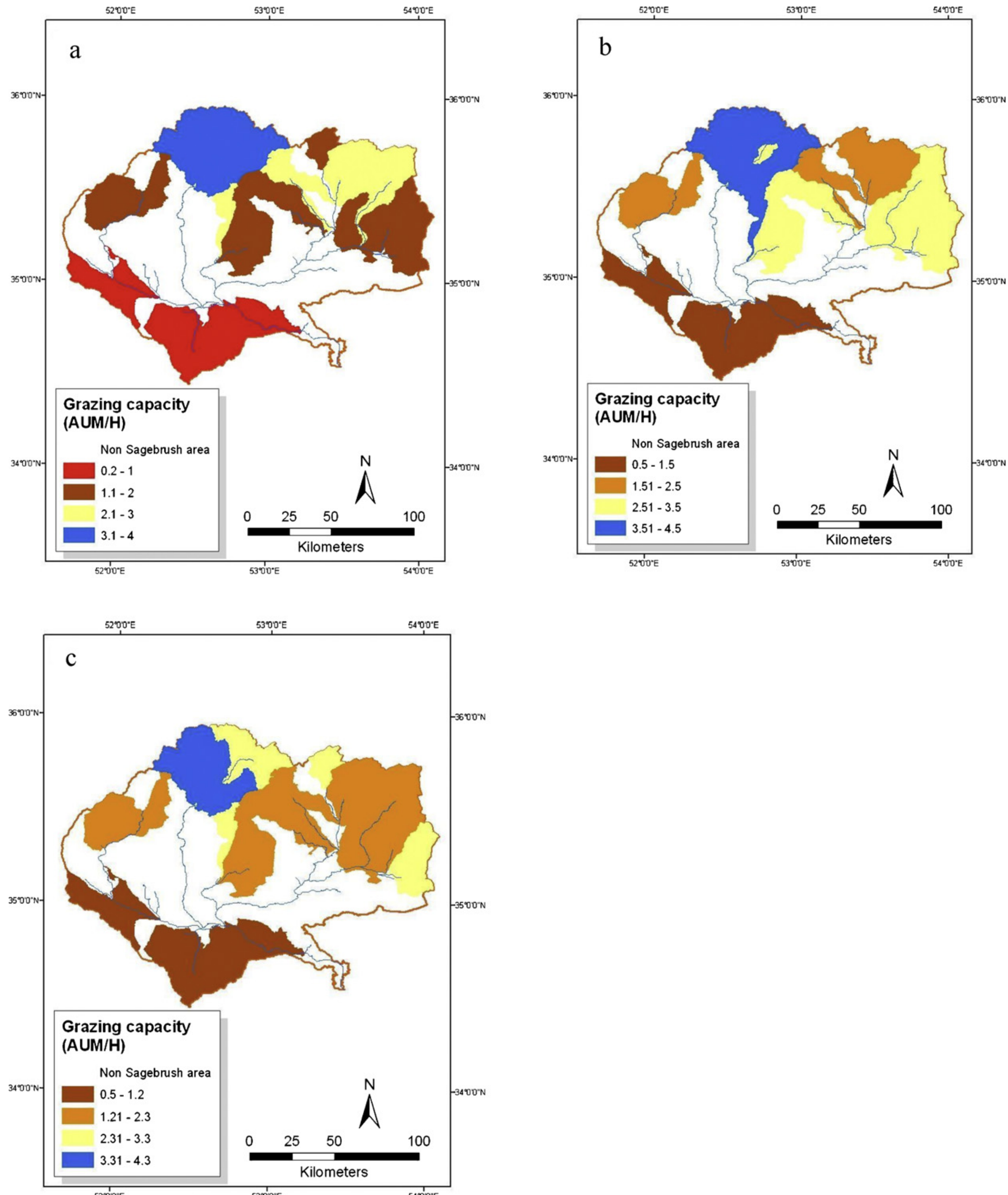

Fig. 9. Grazing capacity maps; actual grazing capacity (a), grazing capacity under water management (b), grazing capacity under grazing management (c).

4. Summary and conclusion

Predictions of forage production, leaf area index, water resources availability including actual ET as well as soil water under different climatic conditions, were performed for Hablehroud river basin at the sub-basin spatial and monthly temporal resolutions. A newly developed program "Critical Continuous Day Calculator" (CCDC) was used to determine the frequency and length of critical precipitation and soil moisture periods. In this paper we modeled forage production and grazing capacity of livestock using SWAT2009. Overall, the plant growth and grazing model of the SWAT performed well in predicting forage production, LAI, and river discharge. A total of 53 discharge, forage production, and grazing parameters were calibrated. Considering the scale of the basin, lack of water use data, and water management practices the results are satisfying and provide notable insight into the water availability, dry period events, forage production, and associated uncertainties in Hablehroud river basin.

This study will be extended to predict the rangeland production of the entire country, which provides the basis to assess the feasibility of alleviating drought induced livestock losses through forward looking forage planning. The analytical framework in this study can be used for the assessment of forage production and livestock management toward sustainable forage production in arid and semi-arid environments. In the next step we will assess the impact of climate change on forage production using the calibrated model in this study.

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