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Effects of different management regimes on soil erosion and surface runoff in semi-arid to sub-humid rangelands

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A B S T R A C T

Over one billion people's livelihoods depend on dry rangelands through livestock grazing and agriculture. Livestock grazing and other management activities can cause soil erosion, increase surface runoff and reduce water availability. We studied the effects of different management regimes on soil erosion and surface runoff in semi-arid to sub-humid rangelands. Eleven management regimes were assessed, which reflected different livestock grazing intensities and rangeland conservation strategies. Our review yielded key indicators for quantifying soil erosion and surface runoff. The values of these indicators were compared between management regimes. Mean annual soil loss values in the '*natural ungrazed*', '*low intensity grazed*', '*high intensity grazed rangelands*' and '*man-made pastures*' regimes were, respectively, 717 (SE = 388), 1370 (648), 4048 (1517) and 4249 (1529) kg ha^{-1} yr^{-1}. Mean surface runoff values for the same regimes were 98 (42), 170 (43), 505 (113) and 919 (267) m^3 ha^{-1} yr^{-1}, respectively. Soil loss and runoff decreased with decreasing canopy cover and increased with increasing slope. Further analyses suggest that livestock grazing abandonment and '*exotic plantations*' reduce soil loss and runoff. Our findings show that soil erosion and surface runoff differ per management regime, and that conserving and restoring vulnerable semi-arid and sub-humid rangelands can reduce the risks of degradation.

1. Introduction

Drylands cover about 41% of the Earth's land surface and are inhabited by more than two billion people, of which 90% live in developing countries (UN, 2011). Over one billion people in these areas depend directly on drylands for their livelihoods, mostly through livestock grazing (65%) and agriculture (25%) (MA, 2005; UN, 2011). Although livestock grazing in drylands contributes to less than 20% of the global meat and dairy production, half of the world's livestock is supported by drylands' natural productivity (MA, 2005). The aridity index (AI) (i.e. the ratio between annual precipitation (P) and annual potential evapotranspiration (PET)) characterizes drylands, which occur in areas where AI ≤ 0.65 (i.e. PET is at least 50% larger than P) (Middleton and Thomas, 1997). Drylands are thus limited by soil moisture resulting from low rainfall and high evaporation.

Twelve to seventeen dryland major types are distinguished, aggregated into four 'broad' biomes: desert, grassland, Mediterranean scrubland, and dry woodlands (MA, 2005). These biomes largely follow the aridity gradient: AIs of hyper-arid, arid, semi-arid and sub-humid drylands range, respectively, from less than 0.05, 0.05 to 0.2, 0.2 to 0.5 and 0.5 to 0.65 (Middleton and Thomas, 1997). In this study we focus on semi-arid and sub-humid drylands and will refer to them as 'rangelands', unless specified differently.

Land degradation is a common threat to semi-arid and sub-humid rangelands. Population increase, climatic variations and human activities (i.e. management) drive land degradation (MA, 2005; UN, 2011). Degradation refers to reduced or lost biological or economic productivity and complexity of both natural and managed rangelands (MA, 2005). Approximately one fifth of all rangelands are currently suffering from degradation (MA, 2005). Rangelands are dominated by grasses, forbs, shrubs and dispersed trees (Westoby et al., 1989). Rangelands are often associated with grazing and managed by ecological or low intensity management

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(Jouven et al., 2010). Most rangelands are grazed by livestock but some rangelands are grazed by natural grazers (Jouven et al., 2010). Semi-arid and sub-humid rangelands cover 56 million km^2 globally (UN, 2011) and are sensitive to management effects and climate variability. Sub-humid rangelands are, due to their higher water availability, increasingly used for intensive livestock grazing and cropping. Semi-arid rangelands, especially in the Mediterranean, have been grazed since the late 1900s (Perevolotsky and Seligman, 1998). This relatively ‘recent’ disturbance has resulted in a transition from grass-dominated to shrub-dominated rangelands and has led to increased rain-induced soil erosion and increased surface runoff (Perevolotsky and Seligman, 1998; Stringham et al., 2003).

The effects of rangeland management and land-use change on degradation and agricultural productivity are poorly understood (UN, 2011). Preventing soil erosion and runoff is crucial to reverse degradation and improve productivity. Reports by MA (2005) and TEEB (2010) acknowledged this by including soil erosion prevention and water flow regulation as important ecosystem services (i.e. the contributions to human wellbeing). Both ecosystem services depend on similar underlying ecological characteristics (Fu et al., 2011). Soil erosion prevention reduces loss of productive land, downstream water pollution, clogging of waterways, flood risk and improves productivity (Snyman, 1999; Fu et al., 2011). Reducing surface runoff provides similar benefits, as well as constant water availability to vegetation, decreased sedimentation and nutrient loss (Narain et al., 1997; van Luijk et al., 2013). Rangeland management is a crucial factor to consider because it negatively or positively affects soil erosion and runoff.

This study assessed the consequences of management decisions in semi-arid and sub-humid rangelands by studying the effects of different management regimes on soil erosion and surface runoff. Management regimes are ‘the bundle of human activities that serve land-use purposes’ and reflect different land-use intensities. Despite the vast scientific consensus on the impacts of different livestock grazing intensities, many vaguely defined and even subjective categories can be found in the rangeland literature, ranging from ‘proper’ to ‘somewhat overgrazed’ (Smith, 1940), ‘moderate’ (Snyman, 1998), ‘heavy’ and ‘very heavy’ (Dormaar et al., 1994; Mwendera and Saleem, 1997). We developed a comprehensive typology of management regimes in semi-arid and sub-humid rangelands, based on eight qualitative management indicators. We also identified indicators for quantifying soil erosion and runoff, based on a targeted review of peer-reviewed papers. Quantifications from these studies were then used to establish mean values of soil erosion and runoff related to different management regimes. In our analysis, we focused on regimes differing in livestock grazing intensities, as well as rangeland restoration and conservation. By comparing different management regimes we identified regimes with the least erosion and optimal runoff and, thus, quantified the related ecosystem services.

2. Methods

2.1. Indicator selection for quantifying soil erosion and surface runoff

We consulted well-cited review papers on soil erosion and/or surface runoff, which resulted in an overview of recurring indicators to quantify soil erosion and runoff indicators for soil erosion and runoff. These papers were by Kosmas et al. (1997), Cantón et al. (2001), Fu et al. (2009), García-Ruiz (2010) and Fu et al. (2011). We then consulted publications that were either citing or cited by these five review papers, thereby focussing on papers that quantified livestock and rangeland restoration management effects on soil erosion and/or runoff. Only indicators that recurred in the literature were included in our overview of indicators, which is provided in Section 4 (including further references) and formed the basis for the analysis that is described in Section 2.3.

2.2. Developing a management regime typology

Our management regime typology included five broad categories, based on Alkemade et al. (2013): ‘natural’, ‘low intensity use’, ‘high intensity use’, ‘converted’ and ‘abandoned’. Each management regime should consist of distinguishable land-use activities, and resulting land cover and specific ecological and socio-economic characteristics. Land use is the purpose for which humans change land cover to their own benefit (Verburg et al., 2011). Land use is enabled by a series of activities, which comprise the management regime (Van Oudenhoven et al., 2012). Land cover refers to all physical biotic and abiotic components that make up landscapes, including vegetation, soils, cropland, water and human structures (Verburg et al., 2011). Moreover, management regimes are assumed to be hard to reverse and transitions from one regime to another require substantial time, investments and management actions (Westoby et al., 1989). With this in mind, further information was needed to select indicators that would help distinguishing different regimes.

A targeted literature review on Web of Science™ was conducted, using the keywords ‘semi-arid’ OR ‘*sub-humid* OR ‘dryland’ combined with ‘*grazing’ OR ‘livestock’ OR ‘rangeland’ OR ‘land use’ OR ‘ecology’ OR ‘*degradation’ OR ‘*management’. Papers were selected from the top-50 most relevant search returns and checked for management indicators and potential management regime categories. We only considered studies dealing with livestock grazing and nature conservation (e.g. restoration, protection, abandoning grazing, reversing erosion) in rangelands and converted rangelands in semi-arid or sub-humid areas. However, an additional search was required to identify indicators for *overgrazed, abandoned rangelands and silvo-pasture*. The studies' aridity zone was verified using a 10’ ‘Global map of aridity’ (FAO, 2014). Locations were approximated when limited information was provided. When aridity zones mentioned in the study's site description did not match ours, we used the studies' original description if the study sites were located between two aridity zones or if the study was conducted before 1990. We ignored the study's description if the site was located more than 300 km away from the claimed aridity zone. We reviewed suitable studies to find indicators for different management regimes, which are summarised in Table 1.

Several assumptions were made to make the indicators applicable to a large variety of rangeland ecosystems and to cope with different ways how rangeland management and land use are described. No quantitative ranges were determined for stocking rate intensities, because these depend on local factors that differ throughout the world's rangelands. Intermediate classes between low and high, and high and overgrazing were ill-defined and highly variable, and thus not considered. Many studies also report the ‘rangeland condition’ and/or vegetation cover in response to different intensities of grazing without referring to actual stocking rates. These indicators are frequently used in traditional rangeland ecology studies (e.g. Snyman, 1997; Puttick et al., 2011). Rangeland condition and/or vegetation cover approximate stocking rates. For instance, poor, good and degraded rangelands could generally be linked to low, high and overgrazed stocking rates, respectively (Snyman, 1997; Fynn and O'Connor, 2000). Rangeland condition involves ecological status (i.e. botanical composition and cover, and plant successional status, productivity, nutritive value and palatability) (Snyman, 1999). Water use efficiency, above-ground