Journal of Arid Environments 142 (2017) 11–21

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Rainfall validates MODIS-derived NDVI as an index of spatio-temporal variation in green biomass across non-montane semi-arid and arid Central Asia

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ARTICLE INFO

Article history:
Received 12 December 2016
Received in revised form
9 February 2017
Accepted 15 February 2017
Available online 11 March 2017

Keywords:
NDVI
Validation
Precipitation
Asian Houbara
Extensive grazing
Pastoralism

ABSTRACT

As satellite-derived normalized difference vegetation index (NDVI) is related to vegetation biomass, it may provide a proxy for habitat quality across extensive species ranges where ground-truth data are scarce. However, NDVI may have limited accuracy in sparsely-vegetated arid and semi-arid environments due to signal contamination by substrate reflectance. To validate NDVI as a vegetation proxy in the low-altitude deserts of Central Asia, we examine its response to precipitation across the migratory corridor of Asian Houbara *Chlamydotis macqueenii*, a threatened gamebird occupying deserts from the Middle East to China. Restricting NDVI data by altitude (masking higher elevations unoccupied by n = 61 satellite-tracked houbara) and 2009 Globcover land cover (excluding cropland and built-up area), we relate moderate-resolution imaging spectroradiometer (MODIS) NDVI data to Global Precipitation Climatology Project precipitation data across five World Wildlife Fund semi-arid ecoregions (totaling 4.06 million km^2). We examine this both spatially (per 1°cell, mean annual NDVI and mean precipitation over 16 years, 2000–2015); and temporally (annual NDVI and annual precipitation) using separate temporal General Linear Models per cell and an overall Generalized Linear Mixed Model (GLMM) (including cell ID as a random effect). We sought to explain spatial variation in the NDVI-precipitation relation among temporal per degree-cell models, in terms of the slope (strength) and adjusted (adj.) R^2 (explanatory power), using inter-annual mean NDVI (2000–2015) and Gridded Livestock of the World livestock density. NDVI increases with precipitation, both spatially (adj. $R^2 = 0.58$, $p < 0.001$) and temporally (mean adj. R^2 across n = 244, 1° cells = 0.44; GLMM across cells $p < 0.001$). More vegetated regions show a stronger temporal response of vegetation biomass for a given precipitation increment (slope of NDVI to precipitation in per cell temporal models increases with inter-annual mean NDVI; adj. $R^2 = 0.38$, $p < 0.001$), reinforcing the conclusion that NDVI provides a proxy for vegetation abundance. The slope of this relation did not differ among ecoregions. Although livestock density is generally assumed to degrade vegetation and weaken the NDVI-precipitation relationship, explanatory power (adj. R^2 of per cell NDVI-precipitation models) is weakly, but positively, related to livestock density (adj. $R^2 = 0.02$, $p = 0.011$). This may be because we assess livestock at a coarse grain, at scales where overall stocking density is positively associated with vegetation abundance, but may also indicate that livestock are not degrading vegetation at regional landscape-scales despite potential localized effects. The strong signature of rainfall shows MODIS NDVI offers a potentially powerful proxy for spatial and temporal variation in arid and semi-arid vegetation at a resolution of 1° and 1 year over the houbara's breeding and wintering range, and probably also at finer spatial resolutions. NDVI can therefore be used in analyses relating (a) staging and wintering site selection to variation in habitat among potential wintering locations, and (b) variation within and between localities to demographic carry-over effects.

1. Introduction

The Normalized Difference Vegetation Index (NDVI) is a remotely sensed, freely-available proxy for green leaf biomass and

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http://dx.doi.org/10.1016/j.jaridenv.2017.02.005
0140-1963/

leaf area index, related to primary productivity (Tucker and Sellers, 1986). It supports a mechanistic understanding of how species respond to climatic and environmental change, thus offering predictive potential. Global coverage and multi-decadal timespans make NDVI data a powerful ecological tool (Pettorelli et al., 2011, 2005) which has helped explain migration patterns (Bridge et al., 2016; Saino et al., 2004a; Tøttrup et al., 2008), life history traits (Saino et al., 2004b) and avian survival (Grande et al., 2009; Schaub et al., 2005). As NDVI responds to climatic and environmental change, it can be used to predict how changing precipitation under future climate scenarios may affect vegetation structure and productivity (Yang et al., 2014), and thus habitat quality and species distributions (Hu and Jiang, 2011; Singh and Milner-Gulland, 2011). However, the information content and explanatory power of NDVI as a proxy for vegetation productivity, indicated by the degree of correlation with precipitation (Weiss et al., 2004) or soil moisture (Yang et al., 2014), can vary geographically owing to varying signal contamination by background reflectance. Geographic inconsistency in NDVI performance makes it problematic for measuring climatic and environmental change, or as a consistent predictor of species distributions when considered at inter-regional rather than localized scales. Lower accuracy in some areas may cause the link between NDVI and species distributions to break down (Parra et al., 2004; Pettorelli et al., 2006). Consequently, the performance of NDVI should be validated across relevant spatial extents, prior to use in ecological research.

NDVI signal contamination from canopy gaps and background conditions can vary with precipitation gradients, snowfall, litterfall, soil organic matter content and substrate mineralogy (Huete et al., 1999), so that the responsiveness of NDVI to vegetation productivity varies geographically. NDVI is affected by differences in soil brightness even for constant vegetation cover, particularly when this is less than 50% (Huete and Jackson, 1985). Therefore, NDVI may have limited application in sparsely-vegetated arid and semi-arid environments with abundant exposed substrate, even though problems from clouds, atmospheric effects, and signal saturation are less in such regions (Gamon et al., 1995; Kaufman et al., 1992). However, as many desert species are sparsely distributed over large ranges, making it challenging to obtain extensive field-based measures to model occupancy, demographic performance and thus habitat suitability, the potential to use NDVI as a proxy could be extremely valuable. If reliable, NDVI could potentially be used to aid the study and conservation of a suite of taxa associated with difficult-to-access semi-arid regions of the Middle East and Central Asia, such as Asiatic Cheetah *Acinonyx jubatus venaticus* (IUCN Critically Endangered), Goitered Gazelle *Gazella subgutturosa* (IUCN Vulnerable), two subspecies of Asian Wild Ass *Equus hemionus onager* (IUCN Endangered) and *E. hemionus kulan* (Endangered) and Central Asian Tortoise *Testudo horsfieldii* (IUCN Vulnerable). Initial global analysis relating inter-annual NDVI to precipitation over 1982–1990 showed significant and positive correlation in semi-arid regions overall, but a non-significant correlation in most of Central Asia (Ichii et al., 2002). More recent studies of Central Asia, with greater sample size (spanning 1980s–2000s) showed a positive NDVI-rainfall correlation that, however, varied between land use/cover types (Nezlin et al., 2005; Propastin et al., 2008; Gessner et al., 2013). If both (a) the extent to which precipitation, as a proxy for potential vegetation productivity, explains observed NDVI and (b) the error or uncertainty in this signature can be related to landscape processes, this understanding of regional variation in NDVI-precipitation signature can assist the interpretation of NDVI and inform the scale at which it should be used (e.g. intra- or transregional). We expect that within arid to semi-arid areas those with relatively greater vegetation biomass (greater mean NDVI) will be more strongly (i.e. steeper regression slope) and clearly (greater R^2) responsive to precipitation, as there is more plant material to respond. Furthermore, vegetation degradation in areas of high livestock density may make NDVI less responsive to precipitation (provided livestock impacts are extensive relative to NDVI measurement grain) (Prince et al., 1998; Li et al., 2004).

To examine whether NDVI offers a potentially useful signal of vegetation productivity and semi-arid habitat structure across non-montane Central Asia, we examine its relationship with precipitation across the migratory range of a population of Asian Houbara *Chlamydotis macqueenii* (IUCN Vulnerable: BirdLife International, 2016) from the southern Kyzylkum Desert, Uzbekistan. Asian Houbara occupy vast and remote desert regions from the Middle East to China, and birds from Uzbekistan follow a similar migration as birds from East Kazakhstan along a "flyway" through Turkmenistan and around the Hindu Kush to wintering areas in southern Afghanistan, Pakistan, and Iran, where birds from China also winter (Combreau et al., 2011). NDVI could offer a proxy that may help understand constraints and settlement decisions on migration (routes and stopover sites), potential inter-annual variation in individual migration choices due to variations in rainfall, and carry-over effects of wintering site quality (Daunt et al., 2014; Rushing et al., 2016) on subsequent breeding productivity and survival. Across a large geographic area encompassing multiple ecoregions, we examine (1) the degree to which NDVI (from 2000 to 2015) relates to variation in precipitation (a) spatially (relating mean NDVI to mean precipitation, among degree cells); (b) inter-annually (within and across degree cells); (2) whether the NDVI-precipitation relation varies between ecoregions; and (3) possible drivers or correlates (mean NDVI and livestock density) of spatial variability in the strength of the NDVI-precipitation relation.

2. Methods

2.1. Study extent

We define our study extent as the outer borders (Fig. 1a) of the migratory corridor and wintering range used by Asian Houbara that breed in Bukhara province, Uzbekistan, and migrate south to winter in Turkmenistan, Iran, Afghanistan and Pakistan (supported by 5 years of satellite telemetry data: Burnside et al., unpublished), together encompassing an area of 4.06 million km^2. Of the several desert and xeric shrubland World Wildlife Fund (WWF) terrestrial ecoregions (Olson et al., 2001) in our study area, we focus on five with varying shrub composition and density (Fig. 1b):

(i) *Central Asian southern desert*, spanning the Karakum and Kyzylkum Deserts of Turkmenistan and Uzbekistan in the north of the study area, where seasonal precipitation is greatest during winter and spring;
(ii) *Central Persian desert basins*, occupying western regions of central Iran and north-west Afghanistan, dominated by a large salt desert in the north and hot sand and gravel deserts in the east;
(iii) *South Iran Nubo-Sindian desert and semi-desert*, occupying a hilly coastal landscape bordering the north of the Persian Gulf on the southern and south-west limits of the study area;
(iv) *Registan-North Pakistan sandy desert*, lying east and south-east of the Central Persian desert basin, comprising semi-deserts in southern Afghanistan, sandy desert in Pakistan, and steppes in Iran; and
(v) *Baluchistan xeric woodlands*, lying further east in Pakistan and Afghanistan, with varied climate and topography.