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Assessing the spatial variability of soil surface colors in northern Jordan using satellite data from Landsat-8 and Sentinel-2

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ABSTRACT

In the semi-arid regions of northern Jordan, soil surface colors show gradual variation from west to east. The dominant soil color in the northwest is a dark reddish brown. Toward the east, lighter brown colors dominate, and colors change further to light yellow in the east. These changes coincide with a climatic gradient (mean annual precipitation). Earlier studies showed a close and possibly causal correlation of soil colors (redness), soil weathering intensity, and mean annual precipitation. However, these conclusions were based on a limited number of soil samples. Our study, in contrast, shows the regional variability of soil colors in the context of geomorphological conditions and the climatic gradient. Two thematic maps of soils surface colors depending on verified supervised classification of Landsat-8 and Sentinel-2 data were created. Results show a remarkable similarity of Support Vector Machines (SVM) classification of Landsat-8 and Sentinel-2 in the area, and confirm a strong correlation of red soil color distribution, mean annual precipitation, and geomorphological aspects (depressions leading to higher water availability and thus soil weathering intensity). Accordingly, this approach offers suitable tools for a quantitative investigation of soil color distribution under the consideration of climatic gradients and varying geomorphological conditions.

Introduction

The north-western region of Jordan is located in the transition zone between the Mediterranean climate in the west and the arid steppe and desert to the east. According to the long-term records of mean annual precipitation (Jordan National Geographic Centre, 1984) the precipitation decreases from more than 600 mm to less than 100 mm from west to east (Figure 1). This gradient is matched by the vegetation cover and agricultural crops, which change from forest cover of the region of the Ajloun Mountains over wheat and vegetables to barley. Further east, only irrigated agriculture is possible. On satellite images taken during summer can be recognized that the main vegetation cover is restricted to the area of forest and some irrigated fields in different sectors. Irrigated areas are mainly located in the east. In addition, there are many olive orchards in the western part of the study area, but they disappear to the east with the exception of some irrigated orchard fields.

Such climate-controlled spatial correlations seems to exist not only between precipitation and vegetation cover, but also between average annual rainfall and soil properties. In this context, Lucke and Sprafke (2015) studied a transect (Khanasreh transect) of soil color change (Figure 1), which crosses a rather flat and geomorphological homogeneous plain in the Irbid-Ramtha basin. The area is covered by Red Mediterranean Soils (Terra rossa) of varying types and intensity of red color. They tested various indices expressing the intensity of soil surface redness (Redness rating: RRBW (Buntley & Westin, 1965); RRH (Hurst, 1977), RRT1 & RRT2 (Torrent, Schwertmann, & Schulze, 1980; Torrent, Schwertmann, Fechter, & Alférez, 1983) and RRBT (Barron & Torrent, 1986); based on the Munsell scale and the CIELAB color system. Depending on these results and a model of transitional maghemite-hematite formation (Torrent, Barrón, & Liu, 2006), they suggested that soil color and weathering intensity along the Khanasreh transect correspond to current mean annual precipitation. These results are significant for various questions of soil science in the area, for example regarding the parent material and pedogenesis of Red Mediterranean Soils on limestone (Barrón & Torrent, 2002; Lucke, Kemnitz, Bäumler, & Schmidt, 2014; Lucke & Sprafke, 2015). The genesis of the Red Mediterranean Soils on limestone (1945) has long been debated, and the formation and significance of the red color is still discussed (see e.g. Lucke, Kemnitz, & Bäumler, 2017; references therein).

Since Lucke and Sprafke (2015) used only a limited amount of 8 soil samples from 6 study sites, it is not clear whether their results are valid for the whole of...
northern Jordan, or partly subject to coincidence when choosing the sampling places.

Therefore, their results should be verified at regional scale. For this, remote sensing provides promising possibilities since spectral characteristics of the soil surface convey relevant information about the composition of the substrate (Clark, 1999; Escadafal, Girard, & Courault, 1988; Hill, 1994; Mulders, 1987; Nanni & Dematté, 2006). This principle of remote sensing of soil color has been applied to mapping of soils with different colors in several case studies (Ben-Dor, 2002; Ben-Dor et al., 2006; Rossel & Chen, 2011; Nanni et al., 2014). In southern Jordan, Löhrer, Bertrams, Eckmeier, Protze, and Lehmkuhl (2013) combined the approaches of remote sensing and spectroscopy (in the range of visible spectrum VIS) to map areas with similar spectral characteristics, and to investigate iron oxide weathering at the recent surface.

Our study aims at a precise supervised classification of remote sensing data to create a thematic map of soil surface colors in the region. Two remote sensing datasets (Landsat-8 and Sentinel-2) were used to increase reliability of results. This map can be integrated with other data (such as rainfall, Geomorphology and/or land use) in geographical information systems to monitor the correlation between them. In particular, this work represents a method suited to check the suggested correlation of soil redness and weathering with current mean annual precipitation in northern Jordan at regional scale (see Lucke & Sprafke, 2015).

Study area

Setting and the topography

The investigation region in northern Jordan extends to the east of the Jordan Rift Valley from the highland of the Ajloun mountains over the Irbid-Ramtha basin to the steppe in the east. It is bordered to the north and north-east by the valleys of the Yarmouk River and the Wadi Shallaleh, near the Syrian border line. Toward the east, it meets the northeastern basalt plateau, which is a part of Djebel al-Arab volcano in Syria (Figures 1 and 2). The area where soil colors were mapped in detail begins to the east of the Ajloun mountains and extends from 35° 46' 57" E to 36° 17' 14" E longitude and 32° 15' 45" N to 32° 31' 39" N latitude (Figure 2).

The topography of the main part of the study region is dominated by a gently undulating plain riddled by low hills. Slopes in this area are generally concavo-convex in shape, and up to 53° steep. However, most of the area is flat and of moderate slope gradients, i.e. 18.7% and 63% of the area respectively, whereas 17% of the area has steep slopes and 1.2% has very steep slopes. The elevation ranges between 500 and 1140 m a.s.l. (Figure 2).

Geology

The geology of the area is characterized by limestones. In the west, the Ajloun Group (Middle...
Cretaceous) dominates, which consists of a series of alternating limestone and marly formations, and reaches over 700 m in thickness in northern Jordan (Andrews, 1992). Important outcrops of the Ajloun Group in the study area are the Na’ur and Wadi as Sir Formation (Figure 3). The Na’ur Formation consists of marl and limestone. The Wadi as Sir Formation is a thick-bedded limestone (often marked by karst formation), which is occasionally dolomitic with infrequent amounts of marl and anhydrite.

To the east and northeast of the study area, another group of Late Cretaceous and Early Tertiary limestones crops out (Balqa Group). It consists of various chalk marls, silicified limestones, phosphorite, and bedded chert and limestone deposits (Amman, Alhisa and Umm Rijam Formation). In the northeast of the

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**Figure 2.** Map of the study area in northern Jordan with elevation ranges.

**Figure 3.** Simplified geological map of the study area.
study area, limestones are capped by a basalt plateau (Harrat ash-Sham), which extends from southern Syria across Jordan and into Saudi Arabia. In this part, basalt boulders with alkali-olivine character are predominant (Abdelhamid, 1995; Gharaibeh, 2005; Moh’d, 2000; ŠamāDi, 2000).

**Soils**

The soils of the study region were mapped by the National Soil Survey of Jordan (NSM & LUP, 1993). In the simplified, nation-wide soil map of Lucke, Ziadat, and Taimeh (2013), the USDA (1990) Soil Orders present in the study area comprise Aridisols, Vertisols, and Inceptisols, with the Great Groups Calciorthids, Chromoxererts, and Xerochrepts (Figure 4).

USDA (1990) does not use color as classification parameter anymore. Applying older soil classifications of soils in Jordan that referred to soil color, the Vertisol and Inceptisol orders correspond to the Red Mediterranean Soils of Moorman (1959), while the Aridisol order corresponds to the Yellow Mediterranean Soils and Yellow Soils (Moorman, 1959). These older classifications demonstrate the marked, transitional change of soil colors in the study region (Figures 1 and 4).

**Materials and methods**

The methodology described herein has been developed taking into account that successful classification and interpretation of remote sensing data requires substantial fieldwork to understand their variations. In addition to the description of vegetation, soils, and geomorphology, the acquisition of spectral surface properties is important to capture spectral variabilities of the different soil types.

**Data and materials**

Data from two sensors were used and compared in this study. These data are freely available and have different spectral and spatial resolution. The first data are the Landsat-8 Operational Land Imager (OLI) Level-2 (Surface Reflectance data) imagery downloaded from earth explorer website of the USGS. One scene covered the whole area of interest. The second data are Sentinel-2, downloaded from Sentinel SciHub as level –1C product. From the second data collection, two scenes have been used to cover the whole study area. Considering the date of fieldwork, sample collection was conducted at the beginning of August 2016. The Landsat-8 scene and the two Sentinel-2 scenes were captured on August 13th and on July 15th of the 2016, respectively. Table 1 shows the basic features of all the data used.

The two scenes from Sentinel-2 were sampled at 10 m resolution using Nearest Neighbor method. A mosaic of the two scenes was produced after using Sen2Cor processor in SNAP Toolbox (ESA) to conduct atmospheric correction and normalization.

Furthermore, we used the digital elevation model from Advance Space Thermal Emission and Radiometer (ASTER) with spatial resolution of 30 m for assessing the role of the geomorphology. Two ASTER GDEM scenes were acquired (ASTGTM2–N32E036, ASTGTM2–N32E035). These data were

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**Figure 4.** Soil map of the study area, after NSM & LUP (1993).
downloaded from the ASTER GDEM Project of Japan-US ASTER Science Team (ERSDAC).

The spectral properties of the soil samples were delineated in the laboratory using the Analytical Spectral Devices (ASD) (Field Spec® 3 Hi-Res). This ASD model allows hyperspectral measurements of specific objects or surfaces in wave spectra ranging from 350 nm up to 2500 nm, namely the visible VIS (350–700 nm), near-infrared NIR (700–1300 nm), and short wave infrared SWIR (1300–2500 nm) wavelength ranges. It works with 8.5 nm resolution in the 1000–1800 nm range and with 6.5 nm resolution in the 1800–2500 nm range.

**Training areas**

To create a reference thematic map of soil (surface) color depending on a supervised classification of remote sensing data, the classifier algorithm needs the worthy definition of Training Areas (TA) in the image, which adequately represent all objects in the study area. Therefore, the choice of TA has been done in three phases:

1. A visual interpretation of images from Landsat-8 and Sentinel-2 defined objects that can be classified.
2. A pre-classification based on visual interpretation.
3. Fieldwork and soil sampling for calibration of classification.

Using true and false color composite images from Landsat and Sentinel-2, just three dominant soil colors in northern Jordan can be recognized: red, bright red soils (BRS); light colored soils; brownish (LBS) and yellowish (LYS) soils (Figure 1). In order to capture the previously transect of soil colors variability in the region (Lucke & Sprafke, 2015), fieldwork followed the same transect that had been studied by Lucke and Sprafke (2015: Khanasreh transect), and collected samples from the same positions using identical coordinates. In addition, further soils were sampled during our intensive survey in the whole region. This was done with the aid of Google Earth high-resolution images.

These phases were followed by a more detailed specification of the TA in the laboratory using spectral reflectance curves of the soil samples. The spectral reflectance values and the shape of spectral curves were examined in the context of the respective literature (Demattê, Bellinaso, Romero, & Fongaro, 2014; Stoner & Baumgardner, 1981). This last step was crucial because the determination of colors in the aforementioned three steps was based only on visual interpretation.

**Soil sampling and reflectance measurements**

Bulk soil samples were collected in order to verify spectral differences between the soils in areas with different surface colors using ASD spectrometer. Samples were collected from a field in every predefined area of interest (12 Sites), mostly covering arable land. Aiming to represent at least a ground coverage of one pixel from Landsat images, 30 m² with samples positioned on the four corners of the square (A, B, C, and D) were used. This distribution of sampling allows the covering of more than one pixel in the Sentinels-2 images.

The collected material (48 Samples) was stored in freezer bags. In addition, control samples were taken from limestone quarries to compare their spectral curves with spectral curves of the soil samples. We noticed in the field that several parts of the area are under the influence of limestone dust, which comes from the quarries or natural limestone exposures. In order to minimize measurement errors associated with stray light, the ASD High Intensity Contact Probe was used to carry out all spectral measurements (Figure 5). The so-called splice correction of spectral curves performed using ViewSpec Pro software from ASD. The median spectral curve of each area of interest was calculated using spectral math of ENVI from measurement results of A, B, C, and D from all areas.

**Satellite data classification**

The classification routine used herein is the Support Vector Machines (SVM) in ENVI software. The SVM algorithm is a machine learning classification algorithm

### Table 1. Basic features of all the data used in this study.

| Band   | Wavelength range (nm) | Spatial ground resolution |
|--------|-----------------------|--------------------------|
| Ultra-Blue | 435 – 451            | 30m                      |
| Blue   | 452 – 512             | 30m                      |
| Green  | 533 – 590             | 30m                      |
| Red    | 636 – 673             | 30m                      |
| NIR    | 851 – 879             | 30m                      |
| SWIR1  | 1567 – 1651           | 30m                      |
| SWIR2  | 2107 – 2294           | 30m                      |
| Blue   | 439 – 535             | 10                       |
| Green  | 537 – 582             | 10                       |
| Red    | 646 – 685             | 10                       |
| Red-Edge1 | 694 – 714           | 20                       |
| Red-Edge2 | 731 – 749           | 20                       |
| Red-Edge3 | 768 – 796           | 20                       |
| NIR    | 848 – 818             | 20                       |
| SWIR   | 1539 – 1681           | 20                       |
| SWIR   | 2072 – 2312           | 20                       |

Landsat-8 Acquisition date 13.08.2016
Sentinel-2 Acquisition date 15.07.2016
that belongs among supervised nonparametric methods, which means that no particular data distribution is required. The SVM classification is not sensitive to training sample size and does successfully work with limited quantity and quality of training samples (Mountrakis, Im, & Ogole, 2011). This type of classification is generally offering an improved classification result compared to traditional classifiers (Foody & Mathur, 2006; Mather & Tso, 2016; Mountrakis et al., 2011; Pal & Mather, 2005; Tso & Mather, 2009). Therefore, the SVM was clearly optimal for our study.

**Results**

The dates of the fieldwork and satellite data acquisition offer two favorable situations of direct optical remote sensing of soils. At this time, climate conditions are quite dry, the land surface mostly bare of vegetation, and large parts of the area were ploughed (Figure 6).

**Thematic classes determination and classification**

We distinguished two essential soil colors, namely dark red and light brown. This was based on visual interpretation of false color images, fieldwork observations, and the comparison of the characteristics of spectral curves of the sampled soils. These have been subdivided into six classes, which demonstrate independent spectral characters (Figure 6). They include from west to east: red soil west (RSW), light soil in debris areas (LS1), light soil with calcium carbonate dust on the surface (LS2), cultivated light soil in the east (LS3), light yellow soil in the east in areas with basalt boulders (LS4), and red soil in the east (RSE). We distinguished between the RSW and RSE, because the RSE are exclusively present in depressions, and have slightly different spectral curves. Therefore, we expected that these two classes can be well separated by the satellite image classification.

In addition to the TA of the soil color classes (6 classes), discrete land-cover units were defined in the area to attain a successful classification. Accordingly, we selected two units of vegetation as TA, which represent forest in the mountain regions as woody vegetation (WG), and irrigated fields as noon woody vegetation (NWG). Furthermore, we defined a TA of urban areas (URA) and a TA of limestone quarries areas (LQA). Figure 7 shows the resulting thematic maps of classification (level 1), which concluded 10 classes of land surface objects (6 of soils, 2 of vegetation, 1 of limestone quarries areas, and 1 of urban areas).

**Separability and classification accuracy**

The separability between individual classes was calculated using the Jeffries–Matusita distance in ENVI software. The results showed that most pairs of classes have high separability, while variety is between the value of 1.99 and the maximum value of 2. Nevertheless, the separability between Red Soil in the west and the Red Soil in the east was low (Table 2).

The accuracy of classifications results were assessed using confusion matrix in ENVI software by overall accuracy (Congalton, 1991) and Kappa coefficient (Cohen, 1960). The overall accuracy (OA) is the averaged sum of the correct classified pixels proportion per class, and the Kappa coefficient of agreement compares the observed proportion of correctly classified pixels to the proportion that would accidentally be classified as correct. In this study in the case of Landsat-8, the overall accuracy and the Kappa Coefficient were equal to 95.80% and 0.951, and in the case of Sentinel-2 were equal to 97.367 and 0.969, respectively. Table 3 show all values of user’s accuracy and producer’s accuracy.
Post-classification

To improve the quality of classification some post-classification processing has to be applied (Lu & Weng, 2007). Thus, remarks from fieldwork and analysis of spectral curves had been taken into consideration. Accordingly, we used a 3*3-majority filter in the ENVI software to eliminate the noises in the classified images. Generally, a classified product contains noises of single classified pixels or “salt and pepper” (Hester, Cakir, Nelson, & Khorram, 2008). The operation gives center pixel weight to perform majority analysis. This type of post-classification is commonly appropriate to remove land cover clusters that are smaller than an analyst’s minimum mapping unit of interest (Jensen, 2005).

Using combine function in ENVI, the two classes of red soil (RSW and RSE) were combined as a class of red soil (RS) as well as the two classes of vegetation (WV and NWV). Furthermore, the pixels of vegetation, urban areas and of limestone quarries classes were deleted.

The result of this post-classification is the level 2 thematic map (Figure 8), which show exclusively the soil (surface) color classes (5 classes), wherein one class is the red soil (RS) and the others are the classes of light colored soils (LS1, LS2, LS3, and LS4). This thematic map was organized in a relational database in ArcGIS to allow thorough analysis (calculating the areas of different soil surface colors) and interpretation (quantitative and descriptive). The quantitative interpretation required integration of the annual rainfall map in the relational database, and the descriptive interpretation was carried out after combining the soil color thematic map with a digital elevation model (DEM).

Red soil color and precipitation

The mean annual rainfall map was converted from vector to raster data and combined with the thematic map of soil surface colors. The result was a thematic map that contains information about soil color classes and rainfall ranges in any pixel. This thematic map was edited to produce a map of red soil after deleting the values of other soil color classes. Subsequently, raster calculator inside ArcGIS was used to compute the area with red
soil cover in every zone of mean annual rainfall. The area of different rainfall range was also computed, which facilitated the calculation of the red soil ratio in every zone of rainfall (Table 4). The resulting distribution of red soil in percent as diagrams is presented in Figure 9.

**Red soil color and geomorphology**

The landscape in the western part of the studied area, with high percentage of RS cover, is quite even except the small section of the Ajloun Mountains (Figures 8 and 9). In contrast, the RS in the east is scattered in isolated different areas. They are situated in sectors of

![Image](image_url)
undulating relief and in the sectors of flat landscape, which is far in the east of the studied area. During the fieldwork and sampling, we observed that distribution of red soils in that area was limited to wadis and depressions. This observation could be verified using the task of fill sink and raster calculator in ArcGIS to extract a raster data containing two categories (depression and no depression) from the digital elevation model (ASTER GDEM). The combination of this raster with the thematic classified map or color composite image confirmed our field observations (Figure 10).

Discussion

Several surveys were executed to map the soils in Jordan (see Lucke et al., 2013, for a summary of all soil surveys in Jordan). The first important work in this field started in the 1950s, whereby 12 great soil groups at a scale of 1:1,000,000 were recognized (Moorman, 1959). This report applied an older version of soil taxonomy referring to soil color (Baldwin, Kellogg, & Thorp, 1938). A more systematic, nation-wide soil survey using soil taxonomy of 1990 (USDA, 1990) was conducted in 1989–1993 (National Soil Map and Land Use Project of Jordan (NSM & LUP, 1993). Despite the substantial gathered data, these surveys provided only limited results regarding questions such as soil color, soil genesis, parent materials, soil development in the context of climate and land degradation. Although older surveys used color as mapping criterion, they stayed on a descriptive level; the national soil survey made some conclusions on soil genesis possible, but did not use color as a criterion any more (see Lucke et al., 2014, 2013). Therefore, the use of remote sensing techniques (spectrometry) to create a soil color map can be supportive to improve our understanding of soil color in the context of soil types, bedrock, and geomorphology, and may permit predictions of chemical attributes (Demattê et al., 2014; Rossel & Behrens, 2010; Rossel & Chen, 2011; Stoner & Baumgardner, 1981).

The soil surface is generally intensively homogenized by the natural fauna and/or human activity. As a result, the soil surface can often reflect the inner composition of soils (Escadafal & Huete, 1992). In several studies, soil colors were successfully used as attributes of soil mineralogy. For example, the carbonates give soils a light color (Courault, Girard, & Escadafal, 1988), iron oxides (goethite and hematite) give the soil yellowish to reddish colors (Barrón & Torrent, 1986; Schwertmann & Taylor, 1977; Torrent et al., 1983), and organic matter darkens soils (Courault et al., 1988). However, the visual inspection is not well-suited for a specific classification of soil surface colors, although is widely used for soil characterization in the field and for soil classification. It is inadequate for remote sensing because the soil color in the field results from the brain’s perception to the light reflected by soil (Nassau, 1980), where the human eye uses just the visible spectrum, namely within the 0.4 µm to 0.7 µm range. This range is a only limited region of the much larger electromagnetic spectrum.
that is available in multispectral remote sensing. Therefore, the use of spectral curves is much better suited for classifying soil surface colors. These, however, should be combined with visual interpretation of satellite images and field observations (Ben-Dor & Banin, 1994). For instance, we noticed depending on the visual interpretation of satellite images and field observations that many quarries of limestone or freshly
exposed limestone are available in the region. This observation was very important to arrange a class of light soil with calcium carbonate dust on the surface. Just as important was the distinction between two vegetation classes (WV and NWV) at the beginning to refine the classification. Regarding the distinction of red soil color, the sub-ordering of red soils in the west (RSW) and red soils in the east (RSE) was not confirmed by the spectral curves, and the separability of these two classes was relatively low (1.95227176). Therefore, we combined the two classes as a class of red soil (RS).

The spectral curves of soils sampled from the area, particularly those of red soils, show significant sigmoidal shapes (Figure 6). This shape is due to the presence of alteration products of iron oxides, which are very common in soils (Escadafal, 1994). In the study area, pedogenic iron oxide contents vary between 0.5% and 2.5% in most soils (Lucke & Sprafke, 2015). In addition, calcium carbonate contents play a role for spectral curves. The increase of the reflectance values particularly in the light color soils is a result of calcium carbonate effects. This can be deduced from the comparison of their reference spectral curves to the reference spectral curves of limestone from the quarry (Figure 6).

The area calculation of RS cover shows a maximum in the western part of the study area. However, in areas with annual rainfall of more than 500 mm/year, red soil ratios are relatively low (Table 3). This is due to widespread vegetation cover and urban areas in this sector. These negative effects are diminishing toward the east, whereby the ratio of RS is more trustworthy. A remarkable drastic drop of red soil cover can be observed to the east of the 200 mm isohyet (Figure 6).

A slight discrepancy is observed between the two datasets (diagrams of Landsat-8 and Sentinel-2). This can be related to two reasons: first, the difference of spatial resolution, since the pixel dimensions of the data from Landsat-8 are 30 m in all bands used, whereas the pixel dimensions of the data from Sentinel-2 are originally 10 m in visible bands (VI) and 20 m in the visible and near-infrared bands (VNIR). Second, the different acquisition dates may have had an impact, as the Landsat-8 scene was acquired on 13.08.2016 and the Sentinel-2 scenes on 15.07.2016.

The geomorphology plays a role too, but apparently less important and relevant only for the scattering of red soil in the east as isolated areas in wadis and depression. This is most probably a result of increased moisture in the depressions, which should have a similar effect on soil weathering intensity as increasing rainfall in the western part of the study area. Therefore, it can be stated that the remote sensing of red soil cover in northern Jordan shows a very strong correlation of the distribution of these soils and the 200 mm isohyet of current mean annual precipitation, suggesting that the hygric gradient in the area plays a critical role for the presence or absence of red soil color.

Conclusions

The classified soil colors in northern Jordan are based on differences of characteristics through their spectral curves (Spectral Signatures), which were calibrated by field observation and ASD spectrometer measurements of soil samples. High values of overall accuracy and Kappa coefficient as well as the relatively comparable results of Landsat-8 and Sentinel-2 classification support the notion that soil distribution follows a hygric gradient in the area, with a dramatic drop of red soil color in areas with less than 200 mm of current mean annual precipitation. This suggests that soil color and its reflectance properties in the visible and near-infrared region reflect soil weathering intensity as proposed by Lucke and Sprafke (2015). The geomorphology seems to play a role too, since red soil colors beyond the 200 mm isohyet are present only in depressions where water gathers, thus confirming the observation that water and soil weathering are decisive for the formation of red color. Apart from water availability, however, the geomorphology and different bedrocks seem to play no role for the presence of red soil colors on the surface.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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