A new approach for biocrust and vegetation monitoring in drylands using multi-temporal Sentinel-2 images

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Abstract
Drylands, one of the planet’s largest terrestrial biomes, are suggested to be greatly threatened by climate change. Drylands are usually sparsely vegetated, and biological soil crusts (biocrusts) – that is, soil surface

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communities of cyanobacteria, mosses and/or lichens – can cover up to 70% of dryland cover. As they control key ecosystem processes, monitoring their spatial and temporal distribution can provide highly valuable information. In this study, we examine the potential of European Space Agency’s (ESA) Sentinel-2 (S2) data to characterize the spatial and temporal development of biocrust and vascular plant greening along a rainfall gradient of the Negev Desert (Israel). First, the chlorophyll a absorption feature in the red region ($\text{CR}_{\text{red}}$) was identified as the index mostly sensitive to changes in biocrust greening but minimally affected by changes in soil moisture. This index was then computed on the S2 images and enabled monitoring the phenological dynamics of different dryland vegetation components from August 2015 to August 2017. The analysis of multi-temporal S2 images allowed us to successfully track the biocrust greening within 15 days from the first seasonal rain events in the north of Negev, and to identify the maximum development of annual vascular plants and greening of perennial ones. These results show potential for monitoring arid and semi-arid environments using the newly available S2 images, allowing new insights into dryland vegetation dynamics.

Keywords
Biological soil crust, remote sensing, satellite, hyperspectral, multispectral, drylands, continuum removal, phenology

I Introduction

Dryland ecosystems constitute one of the largest terrestrial biomes, occupying up to 40% of the Earth’s terrestrial surface and hosting 38% of the world’s human population (Berdugo et al., 2017). The surface in drylands is often characterized by a sparse vegetation cover embedded in a heterogeneous bare soil matrix. These bare areas are often covered and protected by a complex microphytic community consisting of cyanobacteria, algae, fungi, lichens, mosses and other microorganisms that live in the soil’s uppermost layers (Belnap, 2006). These communities, which are commonly known as biological soil crusts or biocrusts, can cover up to 70% of dryland surfaces. Biocrusts modify numerous physiochemical soil and surface properties, protecting the soil surface from wind and water erosion (Belnap and Gillette, 1997, 1998; Chamizo et al., 2016), stabilizing it (Belnap and Büdel, 2016) and influencing local hydrological patterns (Belnap, 2006). In addition, biocrusts produce complex interactions with flora and fauna, control key ecosystem processes as carbon and nitrogen fixation from the atmosphere (Barger et al., 2016) and they are also involved in the albedo feedback (Rutherford et al., 2017). Therefore, monitoring the spatial and temporal changes in biocrust distribution and state can help to understand ecosystem processes like carbon, nitrogen and water cycling, soil surface stabilization and impacts related to climate change in arid and semi-arid environments (Reed et al., 2016).

Remote sensing optical images (visible (VIS) to shortwave infrared (SWIR)) from spaceborne sensors have been widely used to monitor terrestrial ecosystem functions due to their synoptic coverage of the land surface at fixed intervals. However, monitoring drylands from satellite platforms has been quite challenging because arid and semi-arid regions are usually only sparsely vegetated, and the observed spectral signal is a mixture of soil, biocrusts and vascular plants (annuals and perennials) (Rozenstein and Adamowski, 2017; Weber and Hill, 2016). Remote sensing images at high spectral, temporal and spatial resolution are required to accurately map the spatial distribution of the different dryland components from space. High spectral resolution is helpful to separate the biocrust unique spectral features from that of bare soils (Karnieli and Tsoar, 1995; Rozenstein and Karnieli, 2015). A high
temporal resolution can help in separating different land covers because biocrusts and vascular plants have different phenological cycles: the signal from biocrusts is usually dominant in the beginning of the rainy season when the annual plants have not germinated yet and the perennials are still dry (e.g. Karnieli, 2003). This was already evidenced by previous studies where the distinguishable phenological peaks and partially overlapping cycles of these dryland vegetation components were detected by ground spectral measurements (Karnieli et al., 1996, 1999, 2002; Zaady et al., 2007). A high spatial resolution is expected to reduce spectral mixing effects in the VIS and infrared regions (Qin et al., 2006), thus improving the characterization of the biocrust spatial distribution when their fractional cover (Fc) is low. In the past, several spectral indices have been developed and applied to distinguish biocrusts from background (rocks, bare soils or sand dunes) and map their distribution using multispectral satellite images (Chen et al., 2005; Karnieli, 1997). Most notably, the Crust Index (Karnieli, 1997) was developed for cyanobacteria-dominated areas, based on the assumption that phycobilins in cyanobacteria cause an increased reflectance in the blue region. The Biological Soil Crust Index (Chen et al., 2005) exploits the slope between the green and red spectral regions to identify lichen-dominated biocrusts against vegetation and bare sand. Ground-based spectral measurements and Normalized Difference Vegetation Index (NDVI)-derived values have also been used to link semi-arid ecosystem phenology to biocrust CO₂ fluxes in order to assess the capability to detect biocrust activity from satellite (Burgheimer et al., 2006a, 2006b). Additionally, several studies investigated the use of hyperspectral images to detect and map biocrusts. Weber et al. (2008) demonstrated that airborne hyperspectral sensors may improve the ability of spectral data to discriminate biocrusts from other land cover types by exploiting specific absorption features of photosynthetic pigments and other organic components. They applied the continuum-removal algorithm developed by Clark and Roush (1984) to identify spectral absorption features in the VIS and infrared domain in cyanobacteria-dominated biocrusts in a semi-arid ecosystem in South Africa. In several ecosystems, spectral indices derived from hyperspectral data have outperformed multispectral data in mapping areas dominated by biocrusts at the ecosystem scale (Rodriguez-Caballero et al., 2014, 2017a). However, studies employing hyperspectral imagery have been limited to airborne data over specific areas and biocrust types because hyperspectral satellite systems that provide periodic global observations at limited cost compared to airborne platforms are currently unavailable. Before future hyperspectral missions such as EnMAP (Environmental Mapping and Analysis Program), PRISMA (Hyperspectral Precursor and Application Mission) and HyspIRI (Hyperspectral Infrared Imager) will open interesting perspectives in dryland monitoring, the new European Space Agency’s (ESA) satellite mission, Sentinel-2 (S2), provides unique opportunities for monitoring dryland components from space. S2 delivers global acquisitions of optical images with an unprecedented combination of high temporal, spatial and spectral resolution (Drusch et al., 2012). Starting from March 2017, two identical satellites in the same orbit provide high spatial resolution (20 m at full resolution range) multi-spectral images with a temporal resolution of five days at the equator (Berger et al., 2012). S2 is very promising for dryland monitoring, since its high temporal resolution can capture surface phenology subtleties like the greening of biocrusts occurring after rainfall events, before that of vascular plants. Moreover, its spectral resolution – eight bands within the spectral range 490–865 nm – allows a characterization of the typical absorption feature of chlorophyll a shown by all types of biocrusts (i.e. cyanobacteria, algae, moss and lichens) deepened during biocrust greening. S2
spatial resolution is still coarse for capturing the reflectance signal of small patches of biocrusts but good enough for areas where biocrusts cover, to a large extent, the soil, even when mixed with other vegetation components.

The aim of this study is to examine the potential of the newly available S2 images for characterizing the spatial and temporal development of biocrust and vascular plant greening in drylands (Negev desert, Israel), as a first step towards a better understanding and monitoring of biocrust distribution and productivity from space.

To achieve this, we focused on the following specific objectives: i) to identify a spectral index that is sensitive to changes in biocrust greening but minimally affected by soil moisture; ii) to evaluate the performances of this index when applied to a time series of S2 images for monitoring the phenological dynamics of dryland vegetation components (i.e. biocrusts and vascular plants); and iii) to propose two change detection indicators based on multi-temporal S2 images – the first able to capture spectral changes due solely to biocrust response to water pulses, the second related to the maximum development of annual vascular plants and perennial ones.

II Materials and methods

1 Study area and biocrust collection

The study area is the northern Negev desert, Israel (Figure 1). The vegetation typical of this ecosystem has been widely described by ground observations (Shem-Tov et al., 1999; Zaady et al., 1996, 1997). The main driver of the vegetation distribution is the rainfall, which decreases along the north–south gradient from 325 to 50 mm/y in only 100 km. The 200 mm/y isohyet is considered to form the transition zone between arid and semi-arid deserts (Zaady et al., 1996). This ecosystem is characterized by the presence of macrophytic patches consisting of annual herbs and perennial shrubs and microphytic patches consisting of biocrusts. The precipitation gradient, together with topography (i.e. elevation, slope, aspect) affects the distribution of these patches.

Eight sites along the north–south gradient were used to evaluate the methodology proposed in this study. Their main characteristics including locations, elevations, dominant perennial shrubs and their cover, biocrust composition and their cover, annual plant composition and their cover, and soil types and topography are reported in Table 1 (modified from Zaady et al., 2013). As reported in Shem-Tov et al. (1999), in the frontier area between the northern part of the Negev and the Mediterranean zone (325 to 225 mm/y rain) the dominant shrub is Sarcopoterium spinosum (L.) Spach (Rosaceae) – that is, Lahav, Lahavim and Goral study sites; in the Irano–Turanian area (225 to 125 mm/y rain) it is Noaea mucronata (Forssk.) Acherson et Schweinf. (Chenopodiaceae) – that is, Beer Sheva and Mashash Farm study sites; and in the more southerly Saharo–Arabian area (<100 mm/y rain) it is Hammada scoparia (Pomel) Iljin (Chenopodiaceae) – that is, Wadi Boker, Avdat and Wadi Zin study sites. Annual plants are often closely associated with shrubs and their abundance levels change along the rainfall gradient. They are almost not present in the driest sites, while they adapt to germinate beneath the shrubs and within the cracks of the biocrusts in the semi-arid region of the northern Negev. The dominant species depend on the rainfall amount: Stipa capensis is the most abundant species in years with low rainfall amount, and Reboundia pinnata in years with above-average rainfall amount (Shachak et al., 2008). The biocrust communities change along the rainfall gradient from very light cyanobacterial crusts (mainly Microcoleus vaginatus) in areas with low precipitation, to heavy crusts rich in cyanobacteria, green algae, fungi, mosses and lichens, in areas with higher precipitation. Well-developed biocrusts can be 10–15 mm thick, as reported for the Beer Sheva area (Karnieli,
Mosses are generally present in areas receiving rainfall above 150 mm/y. The liverworts *Riccia atronomarginata* and *R. frostii* (Ricciaceae) are found in regions receiving more than 220 mm of yearly rain. Moss species, such as *Crossidium crassinerve* var. *laevipilum*, *Aloina bifrons* and *Tortula* spp. (Pottiaceae), are well adapted to a dry climate (Zaady et al., 1997). Soil lichens also occur in areas receiving 100 mm/y of rain and may be found on stones and rocks in areas receiving only 50 mm/y rainfall. *Collema* spp. are the most abundant lichen in the soil of areas receiving 200 mm of yearly rain.

Five biocrust samples representative of different biocrust levels of development, as described in Table 1, were collected in the study sites and placed in Petri dishes. One cyanobacterial crust (biocrust 1) typical of relatively dry areas of Negev with rainfall between 60 and 100 mm/y was collected from Avdat. Three well-developed biocrusts typical of relatively high rainfall (> 200 mm/y) areas of the Negev were also sampled: biocrust 2 was a well-developed cyanobacterial crust collected at Mashash Farm, biocrust 3 was a well-developed moss crust collected at Beer Sheva site and biocrust 4 was a well-developed mixed cyanobacterial and moss
Table 1. Description of the eight sites along the north–south gradient, encompassing both arid and semi-arid areas, used to evaluate the methodology proposed in this study. Site name, coordinates, elevation, dominant perennial shrubs and their cover (%), biocrust composition and their cover (%), annual composition and their cover (%), soil types* and topography (Israeli, Food and Agriculture Organization of the United Nations (FAO) and U.S. Department of Agriculture (USDA) classifications) are reported.

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Elevation (m a.s.l)</th>
<th>Dominant shrub</th>
<th>Shrub cover (%)</th>
<th>Biocrust composition</th>
<th>Biocrust cover (%)</th>
<th>Annual composition</th>
<th>Annual cover (%)</th>
<th>Soil type* and topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadi Zin</td>
<td>30°42'36.42&quot;N;</td>
<td>700</td>
<td>Hammada scoparia</td>
<td>10</td>
<td>Cyanobacterial crust: Microcoleus vaginatus, Nostoc punctiforme, Schytonema spp.</td>
<td>90</td>
<td>Negligible (rare)</td>
<td>85</td>
<td>Loess** and fine desert alluvium⁴ on wadi bank (typic torrifluvents, ⁵ calcaric fluvisols⁶)</td>
</tr>
<tr>
<td></td>
<td>34°47'1.02&quot;E</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avdat</td>
<td>30°47'4.08&quot;N;</td>
<td>500</td>
<td>Hammada scoparia</td>
<td>10–15</td>
<td>Cyanobacterial crust: Microcoleus vaginatus, Nostoc punctiforme, Schytonema spp.</td>
<td>85</td>
<td>Individuals (rare)</td>
<td>85</td>
<td>Loess and fine desert alluvial soils⁴ on plateau (torrifluvents, ⁵ fluvisols⁸)</td>
</tr>
<tr>
<td></td>
<td>34°46'11.54&quot;E</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wadi Boker</td>
<td>30°51'37.33&quot;N;</td>
<td>400</td>
<td>Hammada scoparia</td>
<td>10–15</td>
<td>Cyanobacterial crust: Microcoleus vaginatus, Nostoc punctiforme, Schytonema spp., Chroococcus spp. and Calathrix spp.</td>
<td>85</td>
<td>Individuals (rare)</td>
<td>80–85</td>
<td>Loess and fine desert alluvium⁴ near wadi edge (typic torrifluvents, ⁵ calcaric fluvisols⁶)</td>
</tr>
<tr>
<td></td>
<td>34°47'53.52&quot;E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mashash Farm</td>
<td>31°3'47.39&quot;N;</td>
<td>360</td>
<td>Noaea mucronata</td>
<td>10–15</td>
<td>Cyanobacterial crust with sparse mosses. Cyanobacteria: Microcoleus vaginatus, Nostoc punctiforme, Schytonema spp., Chroococcus spp. and Calathrix spp. Mosses: Aloina bifrons</td>
<td>85</td>
<td>Erodium laciniatum, Stipa capensis</td>
<td>Very sparse individuals</td>
<td>Sandy loessial alluvial soils⁴ on shallow slopes (typic torrifluvents, ⁵ calcaric fluvisols⁶)</td>
</tr>
<tr>
<td></td>
<td>34°51'16.35&quot;E</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Beer Sheva</td>
<td>31°13'44.78&quot;N;</td>
<td>210</td>
<td>Noaea mucronata</td>
<td>15–25</td>
<td>Cyanobacterial crust with mosses. Cyanobacteria: Microcoleus vaginatus, Nostoc punctiforme. Mosses: Crossidium crassinene var laevipilum, Aloina bifrons and Tortula spp.</td>
<td>80–85</td>
<td>Stipa capensis, Bromus fasciculatus, Trigonella stellate, T. Arabica, Onobrychis squarrosa, Avena barbata</td>
<td>0–5</td>
<td>Loess and fine desert alluvial soils⁴ on plateau (torrifluvents, ⁵ fluvisols⁸)</td>
</tr>
<tr>
<td></td>
<td>34°38'5.99&quot;E</td>
<td></td>
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<td></td>
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</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Elevation (m a.s.l)</th>
<th>Dominant shrub</th>
<th>Shrub cover (%)</th>
<th>Biocrust composition</th>
<th>Biocrust cover (%)</th>
<th>Annual composition</th>
<th>Annual cover (%)</th>
<th>Soil type and topography</th>
</tr>
</thead>
</table>

*Soil analyses were done at ARO laboratory, Volcani Center, Bet-Dagan, Israel.
**Silty or clayey loamy material that is usually off-white or yellowish brown in color and is chiefly deposited by the wind. Loessial deposits include sandy loess, loessial sand, loess loam, clayey loess and loess that are altered during soil-forming processes.
*a Israeli classification.
*b FAO classifications.
*c USDA classifications.
crust collected at Goral site. Finally, biocrust 5, a crust characterized by few lichens, was collected from Lahavim.

The most abundant species of cyanobacteria was *Microcoleus* spp. (i.e. *M. vaginatus*), combined with some other species of cyanobacteria, such as *Nostoc* spp. (i.e. *N. punctiforme*), *Chroococcus* spp. and *Calothrix* spp. Moss biocrusts were characterized by the presence of *Crossidium crassinerve* var *laevipilum* and *Aloina bifrons*, and the common green algae *Palmella* spp. The lichen biocrust was mainly characterized by *Collema* spp.

3 Laboratory measurements

3.1 Optical properties. Reflectance spectra of the biocrust samples were collected using a hyperspectral imaging spectrometer (Hyperspec VNIR, Headwall Photonics) covering the VIS and near-infrared (NIR) spectral regions (Headwall system) coupled with a point spectrometer (ASD FieldSpec Pro, Analytical Spectral Devices Inc., USA) covering the spectral range from the VIS to the SWIR. The Headwall spectrometer collects spectral radiance in 840 bands (ER) was reached was also calculated together with the amount of rainfall registered (Table 2). The ER is defined as 10–20 mm cumulative rains within 15 days from the first seasonal rain events (Karnieli, 2003).

The global climatic precipitation data, with a resolution of 1 km², were also used to define the precipitation isohyets of the study area and to discuss the maps derived from S2 images. The global climate precipitation map is calculated from gridded monthly precipitation data values collected within the time frame 1970–2000 (http://www.worldclim.org/).

Table 2. Name and location of the meteorological stations closest to the study sites. The date when the first effective rain (ER) was reached together with the amount of rainfall registered and the total yearly rainfall calculated as the sum of the daily rainfall from September 2015 to August 2016 for the first year (TR¹) and from September 2016 to August 2017 for the second year (TR²) are also reported.

<table>
<thead>
<tr>
<th>Meteorological station</th>
<th>Location</th>
<th>Study site</th>
<th>Distance from study site (km)</th>
<th>Amount of effective rain (mm)</th>
<th>Timing of effective rain</th>
<th>TR¹ (mm)</th>
<th>TR² (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avdat</td>
<td>30°47'N 34°46'E</td>
<td>Wadi Zin</td>
<td>10.084</td>
<td>11</td>
<td>27 Dec 2016</td>
<td>119.8</td>
<td>37.8</td>
</tr>
<tr>
<td>Avdat</td>
<td>30°47'N 34°46'E</td>
<td>Avdat</td>
<td>0.371</td>
<td>11</td>
<td>27 Dec 2016</td>
<td>119.8</td>
<td>37.8</td>
</tr>
<tr>
<td>Sede Boqer</td>
<td>30°52'N 34°47'E</td>
<td>Wadi Boker</td>
<td>1.823</td>
<td>14.6</td>
<td>27 Dec 2016</td>
<td>88.8</td>
<td>53.2</td>
</tr>
<tr>
<td>Zomet Hanegev</td>
<td>31°4'N 34°51'E</td>
<td>Mashash Farm</td>
<td>0.906</td>
<td>22.1</td>
<td>19 Dec 2016</td>
<td>170</td>
<td>78.7</td>
</tr>
<tr>
<td>Zeelim</td>
<td>31°12'N 34°32'E</td>
<td>Beer Sheva</td>
<td>11.657</td>
<td>20</td>
<td>19 Dec 2016</td>
<td>246.8</td>
<td>113.1</td>
</tr>
<tr>
<td>Beer Sheva</td>
<td>31°15'N 34°48'E</td>
<td>Goral</td>
<td>6.481</td>
<td>22.3</td>
<td>14 Dec 2016</td>
<td>257.6</td>
<td>131.3</td>
</tr>
<tr>
<td>Lahav</td>
<td>31°22'N 34°52'E</td>
<td>Lahavim</td>
<td>4.837</td>
<td>22.5</td>
<td>13 Dec 2016</td>
<td>411.5</td>
<td>218.3</td>
</tr>
<tr>
<td>Lahav</td>
<td>31°22'N 34°52'E</td>
<td>Lahav</td>
<td>2.379</td>
<td>22.5</td>
<td>13 Dec 2016</td>
<td>411.5</td>
<td>218.3</td>
</tr>
</tbody>
</table>
between 380 and 1000 nm with a 2–3 nm resolution at full width at half maximum (FWHM). The Headwall spectrometer was placed at nadir, 22 cm above the biocrust surface, resulting in a spatial resolution of about 1 mm (Garzonio et al., 2018). Biocrusts were illuminated homogenously at a 30° angle using a collimated light beam from a halogen stable light source (600 W, LOT Quantum Design). The ASD Fieldspec Pro is a high-resolution spectroradiometer that acquires measurements across the spectral range 350–2500 nm, with a spectral resolution of 3 nm at 700 nm, and a sampling interval of 1.4 nm. Its fiber optic was coupled to the Headwall system looking down at the biocrust sample at nadir with a 25° field of view.

Biocrust samples in Petri dishes were evenly irrigated until saturation was reached (about 40 ml of double distilled water corresponding to 6 mm of rainfall). Measurements were taken when dry (T0), 12 hours after wetting and then every 24 hours until biocrusts were back to dry condition for a total of six spectral sampling dates (T1–T5).

Reflectance was derived as the ratio between the radiance reflected by the biocrust surface and the radiance reflected by a calibrated Lambertian Spectralon® panel placed close to the biocrust samples. Three measurements were acquired for each biocrust; each measurement was the average of 10 spectra acquired with an integration time of 38 msec. The Headwall instrument’s dark current signal was measured by manually closing the imaging spectrometer aperture prior to measurement and subtracted from radiance measurements. The same subtraction was performed automatically by the ASD Fieldspec PRO spectrometer.

### Table 3. Specification of the Sentinel-2A spectral bands.

<table>
<thead>
<tr>
<th>Band number</th>
<th>Central wavelength (nm)</th>
<th>Bandwidth (nm)</th>
<th>Spatial resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>442.7</td>
<td>27</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>492.4</td>
<td>98</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>559.8</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>664.6</td>
<td>38</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>704.1</td>
<td>19</td>
<td>20</td>
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<tr>
<td>6</td>
<td>740.5</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>782.8</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>832.8</td>
<td>145</td>
<td>10</td>
</tr>
<tr>
<td>8a</td>
<td>864.7</td>
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</tr>
<tr>
<td>9</td>
<td>945.1</td>
<td>26</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>1373.5</td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>1613.7</td>
<td>143</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>2202.4</td>
<td>242</td>
<td>20</td>
</tr>
</tbody>
</table>

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### 3.2 Fc estimation. The Headwall images were saved as 24-bit RGB TIFF images and the fraction of biocrust cover (Fc) was estimated using the FCOVER function in the open source software CAN-EYE v6 (https://www6.paca.inra.fr/can-eye/). The soil was separated from biological components through thresholds defined with a supervised approach on the Headwall RGB images after applying a color stretching to better contrast the soil background from the biological cover. The soil classification of each biocrust was saved as an image file and the total area covered by soil (A_s) was calculated. The Fc was then estimated as \(1-((A_{tot}-A_s)/A_{tot} \times 100)\), with \(A_{tot}\) being the sample area (about 65 cm², area of the Petri dish). Fc was estimated for all the samples when dry and after wetting. The soil classification images were also used to produce soil and biological component masks that were applied to the Headwall images to investigate pure soil and biological component spectra.

### 4 S2 data acquisition

The full S2 mission comprises twin polar-orbiting satellites in the same orbit (S2A and S2B), phased at 180° to each other. Each satellite carries a multi-spectral instrument measuring reflected radiance in 13 spectral bands spanning from the VIS to the SWIR spectral range (Table 3), with a spatial resolution from...
10 to 60 m depending on the spectral band and a swath width of 290 km. The S2 mission provided a global coverage of the Earth’s land surface every 10 days with the launch of the first satellite (S2A) and from March 2017 every five days with the launch of the second S2 (S2B). For details about the S2 mission, refer to Drusch et al. (2012).

In this study, we used 20 S2A images (i.e. granule identification number T36RXV), featuring a cloud cover lower than 10%, collected between August 2015 and August 2017 (Table 4). Only five cloud-free images were available during the first year (August 2015–August 2016), while 15 images were available on the second year (September 2016–August 2017). This is partially due to cloudier days in autumn–winter 2015–2016, but also due to improvements in the Sentinel ground segment (i.e. it allows all Sentinel data to be systematically acquired, processed and distributed) during the first few months after the launch that resulted in a higher number of acquisitions. The images were calibrated and geographically registered (L1B products) by the ESA S2 Mission Performance Centre. Subsequently, the images were atmospherically corrected using the Sen2Cor processor that produces orthorectified bottom-of-atmosphere-corrected reflectance images according to a set of lookup tables generated via libRadtran (Mayer and Kylling, 2005). The accuracy of the atmospheric correction algorithm was qualitatively checked by comparing the reflectance of pseudo-invariant targets.

### Table 4. Dates of Sentinel-2A image acquisition and image identification number.

<table>
<thead>
<tr>
<th>Date</th>
<th>Image ID</th>
</tr>
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</tr>
<tr>
<td>28/11/2015</td>
<td>S2A_20151128</td>
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<tr>
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<tr>
<td>15/07/2016</td>
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<tr>
<td>13/10/2016</td>
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<td>12/11/2016</td>
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<td>11/01/2017</td>
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<td>10/02/2017</td>
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<td>31/05/2017</td>
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<td>10/06/2017</td>
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<td>S2A_20170829</td>
</tr>
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</table>

5 Elaboration of the laboratory hyperspectral reflectance measurements

Different optical indices were computed from the reflectance measured in the laboratory with both the hyperspectral imaging Headwall and point ASD spectrometers. The NDVI (Rouse et al., 1974) was calculated as equation (1):

$$\text{NDVI} = \frac{(\rho_{783} - \rho_{665})}{(\rho_{783} + \rho_{665})}$$

where $\rho_{783}$ is the reflectance measured at 783 nm and $\rho_{665}$ is the reflectance measured at 665 nm.

The absorption features at specific wavelengths were quantified using the continuum removal (CR) method, normalizing the reflectance spectra to a common baseline (Clark and Roush, 1984). This is achieved by approximating the continuum between local spectral maxima through straight-line segments: a value of 1 is assigned to the local maxima, and a value between 0 and 1 is obtained in correspondence to the absorption features. The CR was calculated at first on the ASD reflectance spectra in order to characterize the spectral absorptions related to photosynthetic pigments, water, cellulose and other organic compounds in the different biocrust samples. The band depth (BD) of
a few specific absorption features (685, 1450 and 1930 nm) was calculated as 1 – CR. Additionally, the CR algorithm was applied to the hyperspectral images acquired by the Headwall spectrometer, and, in particular, to selected biocrust components in order to compare the absorption features of bare soils with those of biocrust biological components (i.e. cyanobacteria, mosses and lichens).

Finally, the spectra were resampled to the S2 resolution and CR was applied. In this case, only the absorption feature related to the presence of chlorophyll a was computed at 664.6 nm (S2 B4 band), interpolating the reflectance between 559.8 nm (S2 B3) and 740.5 nm (S2 B6) as the continuum baseline.

6 Simulation of mixed pixels with different biocrust Fc

Reflectance spectra of various biological composition (i.e. cyanobacteria, mosses and lichens), state (i.e. dry and wet) and relative Fc were simulated in order to analyze their effects on the spectral properties, and in particular on the chlorophyll absorption feature. To do so, pure soil and biological component spectra (i.e. endmembers) were extracted from the Headwall hyperspectral images collected on the dry and wet biocrusts. A linear combination of these endmember spectra was then used to simulate the reflectance of mixed pixels with different biocrust Fc and state (i.e. dry and wet). Two sets of mixed pixel spectra were simulated with increasing biological composition. The Fc of the biological component was changed from 0 to 100% (with a regular step of 10%) using endmember spectra measured on dry biocrusts and then those measured on wet biocrusts. The CR algorithm was then applied to the simulated spectra and the variation of CR chlorophyll absorption feature (CRred) at 685 nm and at 664.6 nm for S2 resampled spectra was evaluated when changing crust composition, state and Fc.

7 Analysis of multi-temporal S2 images

The CR absorption feature and the BD at 664.6 nm (CR665 and BD665) were calculated on the full set of 20 S2A images. The development of greenness signal in the study sites along the Negev north–south gradient was characterized by plotting the average BD665 values of a region of interest of 3 × 3 pixels centered on the site coordinates against daily rainfall distribution and cumulative rainfall data registered at the meteorological stations close to the study sites. The frequency of BD665 values, before the start of the rainy season, during biocrust greening and at peak vegetation greening, were obtained from a buffer radius of 100 m drawn around each study site.

Based on this analysis, two change detection indicators were proposed. Assuming that changes in CR665 due only to biocrust greening should occur within a few days after the first rainfall events, the biocrust greenness index (BGI) was calculated as equation (2):

\[
BGI = \frac{(CR_{665,1} - CR_{665,2})}{CR_{665,1} \times 100}
\]

where CR665_1 is the CR value at 664.6 nm calculated from the S2A image acquired just before the first rainfall events of the wet season, when the biocrusts were still dry, and CR665_2 is the CR value at 664.6 nm calculated from the first S2A image available after the first rainfall events of the rainy season, when the biocrusts were wet. Changes detected between these two dates were attributed mainly to biocrust greening that occurred before annual plant germination. S2A images acquired on 12 December 2016 (S2A_20161212 image) and on 1 January 2017 (S2A_20170101 image) were used to compute CR665_1 and CR665_2, respectively, for the second year of study. BGI was not computed for the first year of study due to the limited number of S2A images available.

A second index related to the maximum development of the vascular plants component after the biocrust greening, the maximum
vegetation development index (MVDI), was defined for the two consecutive years of the study as:

$$MVDI = \frac{(CR_{665 \, dry} - CR_{665 \, wet})}{CR_{665 \, dry}} \times 100$$

where $CR_{665 \, dry}$ is the CR value at 664.6 nm calculated from the dry season images and $CR_{665 \, wet}$ is the minimum value of $CR_{665}$—that is, maximum chlorophyll absorption reached during the wet season. The S2A images acquired on 30 August 2015 (S2A_20150830 image) and on 15 July 2016 (S2A_20160715 image) were used as dry season images for the first and second year, respectively. The S2A images acquired on 7 March 2016 (S2A_20160307 image) and on 12 March 2017 (S2A_20170312 image) were used as wet season images for the first and second year, respectively.

The BGI, MVDI_{2015–2016} and MVDI_{2016–2017} mean values for each study site within a 100-m buffer radius were calculated and values were discussed together with the rainfall data.

III Results and discussion

1 Biocrust Fc and reflectance analysis

The Fc of biocrusts 1, 2, 3 and 4 showed similar values around 50%, while biocrust 5 showed a lower Fc (Fc = 16.5%). Fc slightly increased after wetting the biocrusts (around 5%), reached a maximum within 36 hours and, subsequently, decreased back to the dry state values.

Figure 2 displays the mean reflectance spectra of five biocrusts collected when dry (T0) and the mean reflectance spectra of the biocrusts collected five times (from 12 hours to four days) after wetting the samples. The absorption feature at 680 nm, which is mainly related to the photosynthetic pigment absorption, was shown. Two water absorption features in the SWIR domain were also shown with peaks at 1450 nm and 1930 nm. Their depth was proportional to biocrust water content.

The effects of wetting on the reflectance spectra of biocrusts are shown in more detail in Figure 3(a) and (b), where reflectance and CR absorption features of dry biocrusts (T0) are shown against reflectance and CR of wet biocrusts (T2). The five biocrust communities showed similar spectral features, comprising a mixture of vegetation and soil spectra, but they differed in the overall magnitude of reflectance and in the depth of the absorption features. As the biological component increased, the absorption feature in the red increased, and the overall

\[\text{Figure 2. Mean spectral reflectance (}n=3\text{) of biocrusts acquired with an ASD FieldSpec PRO spectrometer when dry and monitored for five times after wetting (total of 30 spectra). T0: measurements at dry state; T1: 12 hours after wetting; T2–T5: at 24-hour intervals.}\]
reflectance (due to biocrust darkening) decreased with a flattening of the slope of the red edge region (region between the red and NIR), as shown in Rodriguez-Caballero et al. (2015). The least developed biocrust (biocrust 5), with the lowest lichen Fc, was characterized by a very slight absorption feature in the red that resembled a typical bare soil. The CR method also showed an absorption feature between 400 and 500 nm that was related more to soil chemical properties, such as CaCO₃ content (Gomez et al., 2008) than to pigment absorption, since the absorption depth did not change with the biological component increase. A decrease in brightness after wetting was observed mainly due to an increase in soil moisture.

In Figure 4, NDVI, BDₓ685, BDₓ1450 and BDₓ1930 values calculated during the temporal course (T0–T5) are shown. A few hours after wetting, the biocrusts turned green and exhibited considerable absorptions in the VIS region due to the activated photosynthetic pigments. The maximum greenness was reached within 36 hours (T2). NDVI showed typical soil values (around 0.2) when dry and reached maximum values of 0.4 when wet. The spectra showed an absorption feature at 685 nm (BDₓ685 > 0) when biocrusts were dry (T0). This means that red light was absorbed by the biocrusts even when the biocrusts were dry. The absorption at 685 nm became deeper after wetting and then decreased as a function of drying. The change in BDₓ685 between dry and wet conditions was related to the biocrust greening, which, in the case of moss-dominated biocrust, is linked to the physiological activity of biocrust (Graham et al., 2006), while in the case of cyanobacteria- or lichen-dominated biocrust the link with physiological activity is not straightforward (Lehnert et al., 2018; Raanan et al., 2016). Changes in BDₓ685 were quite rapid between the dry and the wet states, and changed slowly during the process of drying. BDₓ1450 and BDₓ1930, typical features related to soil water content, also became deeper after watering the biocrusts and decreased slowly, back-to-dry values were reached at T5. BDₓ1450 and BDₓ1930 were used to monitor the biocrusts in order to know when they were back to dry condition.

A detailed spectral analysis of the different biocrust components – that is, biological and soil – was possible using the high spatial

**Figure 3.** Mean spectral reflectance (spectra in the lower part of the plots) and continuum removal absorption spectra (in the upper part of the plots) of the five biocrusts measured using a FieldSpec PRO spectrometer (n = 3) before wetting (T0) (a) and 36 hours after wetting (T2) (b).
resolution of the Headwall images. In Figure 5, the biocrust images acquired by the Headwall imaging spectrometer are shown, together with the biological component mean spectra and CR absorption features when dry (T0) (Figure 5(a)) and 36 hours after wetting the biocrusts (T2) (Figure 5(b)). The absorption peaks measured using the Headwall sensor were more distinct compared to the ASD spectra that resulted from a mixture of soil and biological components. In cyanobacteria, two absorption peaks were found in the blue region (430 nm and 502 nm) due to chlorophyll a, carotenoid or phycoerythrin presence, while in moss-dominated biocrusts only one peak at 492 nm was distinguished. In the red region, cyanobacteria showed a peak at 630 nm due to phycocyanin and at 685 nm due to chlorophyll a, while moss-dominated biocrusts showed only a 685 nm peak (Weber and Hill, 2016). As already observed in Figure 2, the absorption peaks were more pronounced 36 hours after wetting due to the increased pigment content.

In Figure 6, mean pure soil spectra from the biocrust samples are shown when dry (Figure 6(a)) and 36 hours after wetting the biocrusts (Figure 6(b)). Bare soils showed absorption features between 400 and 500 nm, while no significant absorption feature at 685 nm was shown. The absorptions at 400–500 nm are probably related to the soil chemical properties (Gomez et al., 2008), which overlap with carotenoid and
phycoerythrin features, while no soil chemical features overlap with the chlorophyll a absorption at 685 nm. This confirms that the latter can be a more robust diagnostic feature related to the presence of a biological component developing on the soils, as shown by previous studies (Chamizo et al., 2012; Rodriguez-Caballero et al., 2017b).

The chlorophyll a absorption feature was also detected when resampling the spectra to S2 spectral resolution, as shown in Figure 7. The depth of the peak was lower in S2 resampled spectra, due to the lower spectral resolution (i.e. red band is centered at 664.6 nm and bandwidth is 38 nm) compared to Headwall spectra.

The variation of CR<sub>red</sub> with biocrust composition, state and relative Fc was finally evaluated by simulating mixed pixels with different biocrust Fc. As expected, the CR<sub>red</sub> depth was affected by the crust composition, their state (dry and wet) and the Fc. The change (%) in CR<sub>red</sub> due to biocrust greening – that is, the percentage of variation of CR<sub>red</sub> from dry (T0)
to wet (T2) – was computed on Headwall spectra and S2 resampled spectra and plotted against the Fc (Figure 8). The magnitude of CRred changes induced by biocrust greening was affected by the Fc value, showing higher values for increasing Fc, due to a greater proportion of biological components in the simulated spectra. However, we were not successful in finding a unique relationship that linked the value of CRred change and Fc since this relationship was also affected by other factors influencing biocrust chlorophyll content such as biocrust composition: developed biocrusts (biocrust 2, biocrust 3 and biocrust 4) sampled in the semi-arid area showed larger changes in CRred for high Fc values, compared to less developed biocrusts (biocrust 1 and 5) for the same Fc values.

2 Biocrust and vegetation phenology assessment from S2 images

The temporal course of the BD665 obtained from the 20 S2A images acquired between August

![Figure 6. RGB Headwall images of the biocrusts 36 hours after wetting (first row) and the same Headwall images with biological components masked with black color (second row). Mean pure soil reflectance spectra (in the lower part of the plots) extracted from the biocrust samples are shown together with the continuum removal absorption spectra (in the upper part of the plots) for (a) dry samples and (b) 36 hours after wetting. Biocrust 1 is a cyanobacterial crust typical of relatively dry areas of Negev. Biocrust 2 is a well-developed cyanobacterial crust. Biocrust 3 is a well-developed moss crust. Biocrust 4 is a well-developed mixed cyanobacterial and moss crust. Biocrust 5 is a crust characterized by few cyanobacteria and lichens.](image)
2015 and August 2017 in the study sites along the Negev south–north gradient are shown in Figure 9. The average daily rainfall data registered along the latitude gradient are also reported to better discuss the variations of S2A signal in relation to the phenology of the different components (biocrust, annual and perennial plants) in response to rainfall amount and distribution. Northern sites (i.e. Beer Sheva, Goral, Lahavim and Lahav) were characterized by the presence of more developed biocrusts and vascular plants (Table 1; Zaady et al., 2013). In these sites, the BD$_{665}$ index showed noticeable temporal changes. On the contrary, the southern sites (i.e. Wadi Zin, Avdat, Wadi Boker and Mashash Farm) characterized by less...
developed biocrusts and lower vegetation presence showed less pronounced variations. The temporal course in northern sites showed a clear dependency on the rainfall amount and distribution. BD$_{665}$ values increased from the beginning of the rainy season (25 October 2015 and 13 December 2016), reaching a maximum at the beginning of March when mostly annual and perennial plants contributed to the signal acquired by the satellite (Karnieli, 2003) and decreased when rain stopped (13 April 2016 and 12 April 2017). The BD$_{665}$ temporal course was better characterized in the second year (August 2016–August 2017) because more S2A images were available at the beginning of the rainy season, when biocrust greening is expected. In Figure 10, the second-year BD$_{665}$ temporal dynamics in each study site were plotted together with the daily and cumulative rainfall, over the rainy season, measured at the closest weather station. The BD$_{665}$ temporal dynamic was interpreted according to a conceptual model of the succession of biocrusts, annuals and perennials typical of loess Negev area: the biocrust greening should occur just after the first rain event of the rainy season, reaching its peak within a month from the highest precipitation (Burgheimer, 2006b), while the onset of annual plants occurs after the ER and peaks three to four months after it (Karnieli, 2003). The perennial peak occurs about five months after the rain starts (Karnieli, 2003). The daily distribution and cumulative rain differed along the latitude gradient, with higher values in the northern (i.e. Beer Sheva, Goral, Lahavim and Lahav) compared to the southern (i.e. Wadi Zin, Avdat, Wadi Boker and Mashash Farm) sites. The BD$_{665}$ values observed on 1 January 2017 in the northern sites should capture the biocrust greening, since high daily rains were registered before the 1 January S2A acquisition, inducing biocrust rehydration. The highest BD$_{665}$ values were measured in Lahavim (Figure 10(g)), where biocrusts were characterized by heavy moss with high Fc and where high values of daily rain (12 mm) were registered before the S2A acquisition. High BD$_{665}$ values were also shown in Lahav (Figure 10(h)), which shows characteristics similar to Lahavim. According to the conceptual model of the succession of the

**Figure 9.** BD$_{665}$ temporal course (August 2015–August 2017) measured using 3 × 3 S2 pixels centered on the study site locations. The average daily precipitation (mm) values measured by the Israeli meteorological service along the latitude gradient are reported on the secondary y-axis.
different vegetation components, we might expect that biocrust greening slightly overlaps with the germination of annuals in Goral, Lahavim and Lahav sites, where ER occurred 15 days before the S2A acquisition, but not in Beer Sheva where the ER occurred later. However, the full development of annual plants generally takes about one month depending on the amount of water. Therefore, we can reasonably assume that the eventual contribution of annuals to the S2 signal is very low compared to that associated with biocrust greening. In this period, the perennial shrubs were still dormant so we can exclude any possible overlap with them. On 10 January 2017, the BD$_{665}$ in the northern sites was not significantly different from 1 January 2017. It increased significantly in February after new precipitation events, reaching the maximum on the S2A acquisition of 12 March 2017 when annuals were at their phenological peak, and perennial greening also contributed to the spectral signal. It is interesting to notice that the Beer Sheva site (Figure 10(e)) showed higher BD$_{665}$ than the Goral site (Figure 10(f)).

**Figure 10.** BD$_{665}$ temporal course (August 2015–September 2017) measured using 3 × 3 S2 pixels centered on the study site locations: (a) Wadi Zin, (b) Avdat, (c) Wadi Boker, (d) Mashash farm, (e) Beer Sheva, (f) Goral, (g) Lahavim and (h) Lahav. Daily and cumulative precipitation (mm) measured by the Israeli meteorological service stations closest to the study sites are reported on the secondary y-axis.
even though it is located to the south in the latitude gradient and receives less rain. This may be explained by the fact that the Beer Sheva site is located in the Hazerim air force base. This is a fenced area with very little disturbances inside the enclosure, resulting in extremely developed biocrusts in the base compared to the surrounding area, as demonstrated by Rozenstein and Adamowski (2017).

The southern sites showed significantly lower BD$_{665}$ values than the northern sites, particularly during the second year when the cumulative winter rainfall was much lower (Figure 9). Only Mashash Farm showed a slight increase in BD$_{665}$ values during the rainy season in both years (Figures 9 and 10(d)). Biocrust greening was not detected in the southern sites (Figure 10(a) to (c)), where the BD$_{665}$ values measured on 1 January were not different compared to values measured before the rainy season started. The biocrusts in the southern sites were composed mainly of cyanobacteria. We could assume that biocrusts were dry during the satellite overpass or that the cyanobacteria that activate by migrating to the soil surface in response to wetting events probably did not come to the surface because the soil moisture condition was not stable, but characterized by wet and dry pulses (Garcia-Pichel and Pringault, 2001). The only consistent rain event (about 5 mm) before the S2A acquisition occurred on 23 December. The still high temperature (13–17°C) probably induced a fast water evaporation, with no possibility to detect biocrust greenness on 1 January.

Figure 11 shows the spatial distribution of BD$_{665}$ along the latitude gradient, depicting the change of values from dry conditions (Figure 11(a)) to biocrust greening (1 January 2017) (Figure 11(b)) and at full vegetation development (12 March 2017) (Figure 11(c)). In the northern Negev, above the 200 mm isohyet,
BD$_{665}$ notably increased with the start of the rainy season, as shown by the change in map colors from mainly red (low values) to green–blue (Figure 11(a), (b)). The greening intensity was higher in the Beer Sheva surrounding, in agreement with the high biocrust development in this area. Very slight differences were shown in the South Negev, below the 200 mm isohyet, as the map color changed from red–yellow mostly to yellow. BD$_{665}$ increased significantly along the latitude gradient late in the wet season, due to the contribution of vascular plants (Figure 11(c)).

The visual interpretation of Figure 11 was confirmed by the distribution of BD$_{665}$ values shown in Figure 12. In the northern sites, the frequency of BD$_{665}$ values in the three images showed almost no overlap between BD$_{665}$ values that represent dry state, biocrust greening and full vegetation development, while in the southern sites, BD$_{665}$ values showed a high degree of overlap between BD$_{665}$ values of the three images, meaning that biocrust greening was not detected.

Finally, the BGI, MVDI$_{2015–2016}$ and MVDI$_{2016–2017}$ mean values calculated for each study site are reported in Figure 13. The BGI mean values ranged from 5.4 to 9.8% in the northern study sites, and to values below 1% in the southern sites (i.e. Wadi Zin, Avdat and Wadi Boker), with a value of 1.3% in Mashash Farm. BGI values in the southern sites are low because, as already evidenced, it is probable that the low amount of rainfall prior to the S2A acquisition on 1 January 2017 was not enough to activate biocrusts. We are confident that the current availability of both S2A and S2B observations will increase the number of images, allowing a better characterization of the vegetation phenological cycle in this arid area. Specifically, the improved temporal resolution is expected to confirm if it is possible to capture the small signal from the thin cyanobacterial biocrusts from space when images are acquired.
close to the precipitation event. This would also improve the BGI definition at pixel level, allowing the calculation of the CR_{565,2} from the S2 image acquired on the closest date to the first rainfall event of the rainy season. A better characterization of the biocrust greening distribution along the latitude gradient of the Negev desert could also be achieved through the integration of S2 data with other current multispectral satellite sensors, such as Landsat 8 and Sentinel-3, and future hyperspectral missions, such as EnMAP, PRISMA and HyspIRI. This will ultimately allow a more accurate mapping of the biocrust distribution and their dynamics in drylands through time. However, we are aware of the fact that clear-sky image acquisition just after a precipitation day has a low occurrence probability. In ideal conditions, the satellite overpass would coincide with the first clear-sky day after the rain event.

BGI, MVDI_{2015–2016} and MVDI_{2016–2017} maps are shown in Figure 14, together with the world precipitation map of the study area. BGI (Figure 14(c)) values decreased along the latitude gradient, with higher values where biocrusts were more developed (cyanobacteria, moss and lichens) and precipitation was higher (isohyet > 200 mm/y), and lower values where biocrusts were less developed (simple cyanobacterial crust) and precipitation was scarce (Figure 14(a)). In addition, MVDI values decreased along the latitude gradient as vascular plant coverage and composition decreased from north to south (Table 1). The northern area (i.e. north of Mashash Farm latitude) is characterized by the presence of both perennial and
annual plants, while only perennial shrubs (i.e. mainly *Hamada scoparia*) are present in the area further south than Wadi Boker (Table 1).

MVDI<sub>2016–2017</sub> (Figure 14(d)) values were generally lower compared to MVDI<sub>2015–2016</sub> (Figure 14(b)) in agreement with the lower TR registered in the 2016–2017 winter season compared to the previous year. The first year of study was characterized by almost double TR values in the northern sites and more than double in the southern sites compared to the second year (Table 2).

**IV Conclusions**

In this study, a new approach was proposed and successfully used to characterize the temporal and spatial distribution of biocrust and vascular plant greening in the north Negev desert, Israel. First, the chlorophyll a absorption depth, estimated by applying the CR technique to hyperspectral laboratory images, was confirmed as a robust index that is sensitive to biocrust greening and not to soil moisture content. The index was then applied for the first time to S2A images and has proved to be suitable for phenological monitoring of the Negev dryland vegetation components (i.e. biocrusts and vascular plants). Spatial and temporal variations of the index were interpreted together with the rainfall values registered at meteorological stations close to the study sites. Based on these results, two new indices – BGI and MVDI – were proposed to map changes attributed to biocrust and to vascular plant greening, respectively. BGI successfully enhanced biocrust greening occurring after the first rain events in the northern Negev (the semi-arid region), while the BGI values in the southern arid area were low and challenging to interpret. Since the autumn of 2016 and the winter of 2017 were quite dry, with little precipitation in southern Negev, we can hypothesize that the rain amount was not enough to activate the biocrusts. However, future studies should be performed when more S2 data are available in order to determine the detection limit of the proposed methodology in areas with low-developed biocrust (i.e. cyanobacteria crust) such as in southern Negev.

MVDI showed the variation of vegetation development along the Negev latitude gradient, with clear differences between 2016 and 2017 linked to the different total precipitation registered.

The analysis of BGI and MVDI trends over time will contribute to a better understanding of the impact of climate change on drylands, and, in particular, on biocrust activity since they are known to be especially vulnerable to changing climatic conditions.

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**References**


