Seasonal evolution of soil and plant parameters on the agricultural Gebesee test site: a database for the set-up and validation of EO-LDAS and satellite-aided retrieval models

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Abstract. Ground reference data are a prerequisite for the calibration, update, and validation of retrieval models facilitating the monitoring of land parameters based on Earth Observation data. Here, we describe the acquisition of a comprehensive ground reference database which was created to test and validate the recently developed Earth Observation Land Data Assimilation System (EO-LDAS) and products derived from remote sensing observations in the visible and infrared range. In situ data were collected for seven crop types (winter barley, winter wheat, spring wheat, durum, winter rape, potato, and sugar beet) cultivated on the agricultural Gebesee test site, central Germany, in 2013 and 2014. The database contains information on hyperspectral surface reflectance factors, the evolution of biophysical and biochemical plant parameters, phenology, surface conditions, atmospheric states, and a set of ground control points. Ground reference data were gathered at an approximately weekly resolution and on different spatial scales to investigate variations within and between acreages. In situ data collected less than 1 day apart from satellite acquisitions (RapidEye, SPOT 5, Landsat-7 and -8) with a cloud coverage \(\leq 25\%\) are available for 10 and 15 days in 2013 and 2014, respectively. The measurements show that the investigated growing seasons were characterized by distinct meteorological conditions causing interannual variations in the parameter evolution. Here, the experimental design of the field campaigns, and methods employed in the determination of all parameters, are described in detail. Insights into the database are provided and potential fields of application are discussed. The data will contribute to a further development of crop monitoring methods based on remote sensing techniques. The database is freely available at PANGAEA (https://doi.org/10.1594/PANGAEA.874251).

1 Introduction

Ground reference data are required for the set-up and validation of land data assimilation systems that enable large-scale monitoring of crop properties with Earth Observation data (Lillesand et al., 2008). The recently developed Earth Observation Land Data Assimilation System (EO-LDAS; Lewis et al., 2012) represents a weak-constraint variational land data assimilation system that relies on radiative transfer models describing the interaction of photons with canopy, leaves, and soil. EO-LDAS can be used in two different modes. In the forward mode, the surface reflectance of vegetated areas can be simulated in the visible and infrared domain for a given set of soil and vegetation parameters. In the inverse mode, Earth Observation data are interpreted in terms of soil and vegetation parameters, while prior information is introduced to diminish the uncertainty of retrieved parameters (cf. Chernetskiy et al., 2017).

Ground reference data for retrieval models that make use of satellite observations in the visual and infrared do-
that may also be used in combination with satellite-aided database for the set-up, test, and validation of EO-LDAS. Location of the forward mode. Spectral measurements are required for an in-depth validation necessitates a high temporal resolution. In addition, hyperspectral measurements of surface reflectance factors. The measurement design, equipment, and methods are described in detail. Free access to the database is provided on PANGAEA (https://doi.org/10.1594/PANGAEA.874251, Truckenbrodt and Baade, 2017).

2 Study area and site description

The agricultural Gebesee test site (51°05′ N, 10°55′ E; 150–180 m a.s.l.) is situated in the Thuringian Basin in central Germany (Fig. 1). Low relief energy and the predominance of fertile loess soils promote widespread agricultural land use in the region (Hiekel et al., 2004). Mean annual precipitation is rather low (530 mm; 1991–2014; DWD, 2015) because of rain shadow effects generated by the Thuringian Forest to the south and the Harz Mountains to the north (Bauer, 1959). Mean monthly rainfall varies from about 30 mm in February to about 80 mm in July. Average annual air temperature is about 9.5 °C, while mean monthly temperatures range from 0.8 °C in January to 18.9 °C in July (1991–2014; DWD, 2015). The growing season prevails from March to November, but the duration may vary depending on temperature (TLL, 2009).
Table 1. Cultivation plan for the investigated acreages (see also Fig. 1).

<table>
<thead>
<tr>
<th>Acreage no.</th>
<th>2013 Species</th>
<th>Acreage size</th>
<th>ESU</th>
<th>2014 Species</th>
<th>Acreage size</th>
<th>ESU</th>
</tr>
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<tbody>
<tr>
<td>340</td>
<td>– winter rape</td>
<td>37.02</td>
<td>340-1</td>
<td>Brassica napus</td>
<td>340-3</td>
<td>Exstorm</td>
</tr>
<tr>
<td>350</td>
<td>– spring wheat</td>
<td>41.28</td>
<td>350-1</td>
<td>Triticum aestivum</td>
<td>350-2</td>
<td>Taifun</td>
</tr>
<tr>
<td>340^a</td>
<td>spring wheat</td>
<td>10.33</td>
<td>430-1</td>
<td>Triticum aestivum</td>
<td>430-2</td>
<td>Taifun</td>
</tr>
<tr>
<td></td>
<td>Triticum durum Desf.</td>
<td>9.73</td>
<td>430-2</td>
<td>Floradur</td>
<td>430-3</td>
<td></td>
</tr>
<tr>
<td>440^b</td>
<td>potato</td>
<td>4.04</td>
<td>440-1</td>
<td>Solanum tuberosum L.</td>
<td>440-2</td>
<td>Birgit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>470</td>
<td>winter barley</td>
<td>48.12</td>
<td>470-1</td>
<td>Hordeum vulgare L.</td>
<td>50.73</td>
<td>Souleyka</td>
</tr>
<tr>
<td>500</td>
<td>winter wheat</td>
<td>49.26</td>
<td>500-1</td>
<td>Triticum aestivum L.</td>
<td>500-1</td>
<td>Genius</td>
</tr>
<tr>
<td>771</td>
<td>durum</td>
<td>29.23</td>
<td>771-3</td>
<td>Triticum durum Desf.</td>
<td>8.57</td>
<td>Floradur</td>
</tr>
<tr>
<td></td>
<td>Solanum tuberosum L.</td>
<td>8.57</td>
<td>771-1</td>
<td>Floradur</td>
<td>771-2</td>
<td>Concordia</td>
</tr>
<tr>
<td>820</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>durum</td>
<td>51.68</td>
<td>820-1</td>
</tr>
<tr>
<td></td>
<td>Triticum durum Desf.</td>
<td>51.68</td>
<td>820-1</td>
<td>Floradur</td>
<td>51.68</td>
<td></td>
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<tr>
<td>830</td>
<td>spring wheat</td>
<td>60.49</td>
<td>830-3</td>
<td>Triticum aestivum L.</td>
<td>830-3</td>
<td>Taifun</td>
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<tr>
<td></td>
<td>Hordeum vulgare L.</td>
<td>60.49</td>
<td>830-1</td>
<td>Laverda</td>
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<td></td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>830-3</td>
<td></td>
</tr>
</tbody>
</table>

^a ESU 430-2 intersected a cultivation boundary in 2013: Spring wheat grew on SSP00 to SSP16, while durum grew on SSP24. ^b ESU 440-1 and ESU 440-2 intersected a cultivation boundary in 2013: The cultivar Concordia grew on SSP00, while the cultivar Birgit grew on SSP08 to SSP24.

The Gebesee test site consists of nine acreages ranging in size from 8.57 to 60.49 ha (Table 1). The acreages are situated on fields 340, 350, 430, 440, 470, 500, and 771 in the northern and central parts of the test site and fields 820 and 830 in the south (Fig. 1b; https://doi.org/10.1594/PANGAEA.874249). The northern and central parts are characterized by fertile Haplic Chernozems (according to IUSS Working Group WRB, 2015) that developed on Quaternary loess deposits (Rau et al., 2000; Anthoni et al., 2004). Relief energy is generally low in these areas, with slopes < 2.5° (TLVermGeo, 2008). In the southern part, clayey sedimentary rocks of the Triassic Keuper formation (Rau et al., 2000) are typically associated with Vortic Chernozems (TLUG 2000; TLUG 2002). Here, slope inclination reaches up to 5° (TLVermGeo, 2008). The fields are cultivated based on crop rotation by Geratal Agrar GmbH & Co. KG Andisleben (Geratal Agrar). In 2013 and 2014, all investigated crops were entirely rain-fed. An eddy covariance
Figure 2. Design of elementary sampling units (ESUs). Each ESU contains five secondary sampling points (SSPs). The azimuthal orientation of the ESUs was chosen according to the inclination of the SPOT 5 and Landsat-7 and -8 descending orbits. The figure illustrates the pixel size of images from various satellite sensors in comparison to the size of ESUs. The case with the smallest spatial coincidence between pixels and the ESU is depicted.

3 Measurement design of the field campaigns

Ground reference data were collected for several crop types, i.e., winter barley, winter wheat, spring wheat, durum, and potato throughout the cultivation periods of 2013 and 2014. In addition, data for winter rape and sugar beet were gathered in 2014 (Table 1). The selected crop types cover a wide range of canopy architectures and represent frequently cultivated crops at the mid-latitudes (USDA, 2015). Moreover, these crops are regularly grown on field 430, which occupies the major part of the flux tower footprint (Anthoni et al., 2004). This allows for the combination of current data with flux tower measurements.

Field measurements were carried out on various spatial scales by applying the concept of elementary sampling units (ESUs; Morisette et al., 2006). Up to three ESUs were established for each crop type to investigate spatial heterogeneity on the scale of acreages. ESUs were designed as squares with a diagonal length of 24 m, which occupies the major part of the flux tower footprint (Anthoni et al., 2004). This allows for the combination of current data with flux tower measurements.

Each ESU consists of five secondary sampling points (SSPs) that permit an assessment of spatial heterogeneity on the scale of ESUs. On each ESU, SSPs were established along the 24 m long diagonal running from the southwestern to northeastern corners (Fig. 2). SSPs were located 0, 8, 12, 16, and 24 m from the southwestern corner and are labeled SSP00, SSP08, SSP12, SSP16, and SSP24, respectively. Spacing between SSPs permits the simulation of sub-pixel variability in satellite data acquired with medium resolution sensors carried by RapidEye, SPOT 5, and Landsat-7 and -8. In order to minimize disturbance on acreages and ESUs, measurement points were accessed via tractor lanes and < 0.5 m wide paths leading along the SSPs.

In 2013, acreage 430 was split with spring wheat and durum being cultivated in the western and eastern parts, respectively (Table 1). The split became apparent only after the start of the measurements. ESU 430-1 and SSP00 to SSP16 of ESU 430-2 represent spring wheat, while durum grew...
### Table 2. Overview of surveyed parameters, variable names (as they appear in the database), units of measurement, sampling frequencies, utilized equipment, and methods. When parameters were not regularly ascertained, the total number of measurements per cultivation period is provided in parentheses ("(x)"). Numbers in square brackets ("[x]") refer to differing sampling frequencies on potato fields.

<table>
<thead>
<tr>
<th>Surveyed parameters</th>
<th>Variable name</th>
<th>Unit</th>
<th>S0</th>
<th>S0</th>
<th>S0</th>
<th>S0</th>
<th>S0</th>
<th>S0</th>
<th>ESU</th>
<th>acreage</th>
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<td>Plant h</td>
<td>m</td>
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<td>5</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>–</td>
<td>Folding ruler</td>
</tr>
<tr>
<td>Fractional vegetation cover</td>
<td>FVC</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
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</tr>
<tr>
<td>Prop. of senescent material</td>
<td>PSM</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>–</td>
<td>Digital camera</td>
</tr>
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<td>Plant area index PAI</td>
<td>PA&lt;sub&gt;LA200&lt;/sub&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>LI-COR LAI-2000</td>
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<td>Foliage tilt angle</td>
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<td>1</td>
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<td>1</td>
<td>–</td>
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<tr>
<td>Awn length</td>
<td>Awn l</td>
<td>cm</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(≤ 3)&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Ear inclination</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Folding ruler</td>
</tr>
<tr>
<td>Above-ground biomass</td>
<td>AGB</td>
<td>g m&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Gravimetical</td>
</tr>
<tr>
<td>Fruit yield</td>
<td>Fr yield/acreage</td>
<td>t ha&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(1)</td>
<td>Provided by Geratal Agrar</td>
</tr>
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<td>Harvested AGB</td>
<td>Biom above gr/acreage</td>
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<td>–</td>
<td>–</td>
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<td>(1)</td>
<td>Provided by Geratal Agrar</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>BBCH scale</td>
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<td>–</td>
<td>–</td>
<td>Digital camera</td>
</tr>
<tr>
<td>Leaf chlorophyll content</td>
<td>Chl &lt;sub&gt;a&lt;/sub&gt;</td>
<td>µg cm&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>10</td>
<td>10</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>–</td>
<td>Konika Minolta SPAD-502+</td>
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<tr>
<td></td>
<td>Chl &lt;sub&gt;b&lt;/sub&gt;</td>
<td>µg cm&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<td>–</td>
<td>Konika Minolta SPAD-502+</td>
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<tr>
<td></td>
<td>Chl a + b</td>
<td>µg cm&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>10</td>
<td>10</td>
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<td>10</td>
<td>10</td>
<td>–</td>
<td>Konika Minolta SPAD-502+</td>
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<tr>
<td>Leaf dry matter</td>
<td>Leaf dry mat</td>
<td>g m&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>≤ 3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Gravimetical, digital camera</td>
</tr>
<tr>
<td>Equivalent leaf water</td>
<td>Leaf water</td>
<td>cm&lt;sup&gt;2&lt;/sup&gt; m&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>≤ 3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>–</td>
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<tr>
<td>Soil moisture</td>
<td>wetgrav_SoilMoist</td>
<td>wt %</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<tr>
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<td>vol_SoilMoist</td>
<td>% vol</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>–</td>
<td>–</td>
<td>Gravimetical</td>
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<td>W max</td>
<td>mm</td>
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<td>Volt_out</td>
<td>mV</td>
<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>[5]</td>
<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Estimated soil moisture</td>
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<td>wt %</td>
<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>[5]</td>
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<td>% vol</td>
<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>1&lt;sup&gt;b&lt;/sup&gt; 3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Absolute reflectance factor</td>
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<td>Direct solar irradiance</td>
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<tr>
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<td>Landscape photographs</td>
<td>–</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Digital camera</td>
</tr>
<tr>
<td>GNSS coordinates</td>
<td>Easting/Nothing</td>
<td>m (UTM 32U)</td>
<td>(1)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(1)</td>
<td>–</td>
<td>LEICA GS15, STONEX S9HIN</td>
</tr>
<tr>
<td></td>
<td>Altitude</td>
<td>m (DHHN92)</td>
<td>(1)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(1)</td>
<td>–</td>
<td>LEICA GS15, STONEX S9HIN</td>
</tr>
</tbody>
</table>

For some parameters representative values for ESUs were calculated based on measurements at all respective SSPs (marked with "*"), while for other parameters data are only available on the scale of ESUs. <sup>a</sup>, <sup>b</sup>, and <sup>c</sup> indicate that data acquisition on the specific scale was restricted to 2013 and 2014, respectively.
Field work was carried out with approximately weekly resolution taking into account the local weather forecast. Field measurements were preferentially scheduled for days with a high probability of low cloud coverage, since the occurrence of haze and clouds interferes with hyperspectral measurements (Gilabert and Meliá, 1993). In addition, we attempted to synchronize days of field work with acquisition plans of RapidEye, SPOT 5, Landsat-7, and -8. Measurement frequency differed between parameters and SSPs as shown in Table 2. In 2014, investigations were conducted consistently throughout the cultivation period, while the measurement start varied between different parameters in 2013. Most parameters were surveyed from the beginning of the cultivation period, but the measurement start for plant area index, leaf chlorophyll content, and hyperspectral data was delayed (Fig. 3). Monitoring of equivalent leaf water, leaf dry matter, aerosol optical thickness, and column water vapor was entirely restricted to 2014.

4 Ground measurements

Unless stated otherwise, data for parameters introduced in this chapter are available via the PANGAEA datasets for 2013 (https://doi.org/10.1594/PANGAEA.874158) and 2014 (https://doi.org/10.1594/PANGAEA.874235).

4.1 Biophysical plant parameters

4.1.1 Plant height

Plant height (Plant h) is a key parameter for the description of the canopy architecture in radiative transfer models as it determines the thickness of the layer in which photons interact with plant compartments (Gobron et al., 1997). Plant height was determined with a folding ruler as the distance...
from the soil surface to the top of canopy. At each SSP, five measurements were carried out in a 1 m circuit. A reduction in plant height is determined when ears of cereals are drooping or when cornstalks are flattened before harvesting.

4.1.2 Fractional vegetation cover and proportion of senescent material

Fractional vegetation cover (FVC; Purevdorj et al., 1998) depicts the relative proportion of vegetated areas and is, thus, an indicator of the relative contribution of the soil and vegetation signals to the top of canopy reflectance. The vegetation signal itself varies strongly between green and senescent plant compartments. To account for this, the proportion of senescent material (PSM) was ascertained with respect to the overall vegetated area. FVC and PSM were determined from nadir photos. At each SSP, two nadir photos were taken 1.2 m above the ground and 1 m above the top of canopy, respectively. Photos were alternatively captured with a Nikon D300s (equipped with a AF-S DX NIKKOR 16–85 mm 1:3.5–5.6 ED VR) and a Nikon D5000 (equipped with a TAMRON AF 18–200 mm F/3.5–6.3 [IF] MACRO Ø62 A14) with focal length set to 18 mm. From these photos, FVC and PSM were determined by applying an automatic two-step pixel-based hierarchical classification procedure that was implemented in the R software environment (version 3.2.3; R Core Team, 2015). The following classes of pixels were distinguished: “soil”, “green vegetation”, and “senescent vegetation”.

Nadir photos were acquired under varying illumination conditions. Previous work indicates that hue values are far less affected by illumination conditions than RGB (red, green, blue) values (Liu and Moore, 1990). Thus, all nadir photos were transformed to the HSL (hue, saturation, lightness) color space (Motonaga et al., 2004).

In the first classification step, soil pixels were distinguished from non-soil pixels with the help of a look-up table. A pixel was ascribed to the class “soil” when the saturation fell below a threshold that depends on hue (H) and lightness (L). In the second step, a non-soil pixel was classified as “green vegetation” if the H values fell between 24 and 135 (i.e., a greenish shade) and L exceeded a threshold that depends on H. Remaining non-soil pixels were categorized as “senescent material”. Since small bright soil particles were frequently misclassified as “green vegetation” or “senescent vegetation”, pixels initially ascribed to these classes were clumped together with horizontally and vertically adjacent vegetation pixels and reclassified as “soil” if the related object comprised less than 200 pixels. Afterwards, a circular area with a diameter of 2648 pixels around the principle point of the photo was extracted. This corresponds to circles with diameters of about 1 and 0.85 m on the ground and top of canopy, respectively. Within the masked area, the classification results were evaluated statistically to obtain FVC and PSM which may range between 0 and 1.

Bias and precision of FVC and PSM were assessed separately for each species, based on one arbitrarily selected ESU from which ≥ 10 images were analyzed. In order to take into account different phenological, soil, and illumination conditions, we ensured that the acquisition dates of the selected images were regularly distributed throughout the cultivation period. From each image, a validation set consisting of 300 pixels was created using a stratified random sampling procedure implemented in Geomatica 2013 (PCI Geomatics, 2013). The proportion of pixels from each class in the validation set corresponded to the class percentage in the image according to classification results. All pixels in the validation set were visually inspected and ascribed to the appropriate class to obtain reference values against which classification results were compared. For each image the bias $X_{bias}$ in the determined proportion of pixels representing vegetation $(X = FVC)$ and “senescent vegetation” $(X = PSM)$ was calculated with Eq. (1),

$$X_{bias} = \frac{n_{ClassX} - n_{RefX}}{n_{Refall}},$$  

where $n_{RefX}$ and $n_{ClassX}$ represent the number of pixels which were ascribed to class $X$ by means of visual inspection and automatic classification, respectively; $n_{Refall}$ specifies the number of all pixels that were involved in the validation. Mean and standard deviation of $X_{bias}$ were determined for each species from all considered images and are provided on PANGAEA (https://doi.org/10.1594/PANGAEA.874144).

4.1.3 Plant area index

The plant area index (PAI), i.e., the leaf area index (LAI) including ears and cornstalks (Neumann et al., 1989), is an important canopy structural parameter in radiative transfer models and retrieval models in general (Gobron, 2008). PAI was ascertained in two different ways: (1) with the LAI-2200 Plant Canopy Analyzer (LAI-2200; LI-COR Biosciences, Inc.) and (2) based on digital hemispherical photos (DHPs). Both methods rely on the determination of the gap fraction (Ross, 1981), permit repetitive non-destructive measurements (Morisette et al., 2006), and were deployed complementarily. While PAI values obtained from the LAI-2200 method are available on the scale of SSPs and ESUs, PAI values derived from DHPs are only provided for entire ESUs.

LAI-2200 measurements were carried out following the recommendations of LI-COR (2012) for “row crops”. The gap fraction was determined based on $2 \times 4$ measurements along 0.5 m long transects running diagonally between neighboring planting rows. The sensor lens was covered with a 45° view cap with the field of view (FOV) oriented parallel and orthogonal to the planting rows, respectively. Direct solar irradiance should be avoided in LAI-2200 measurements (LI-COR, 2012). Thus, the sensor and part of its FOV were shaded with an umbrella. Processing of raw data was conducted with the FV2200 software (version 1.2; LI-COR Bio-
The gap fraction was determined in five concentric rings defined by central zenith angles of 7, 23, 38, and 68°. In the course of the calculations uniform distribution of the canopy in the horizontal direction was assumed and the apparent clumping factor (ACF) following Ryu et al. (2010) was applied. The calculations reveal a parameter set including the PAI_{LAI2200} that is close to the “true” PAI (cf. Weiss et al., 2004), PAI standard error (SE PAI_{LAI2200}), fraction of sky (FoS), mean foliage tilt angle (Tilt), and related standard error (SE Tilt; LI-COR, 2012). For the computation of ESU-wide parameter sets with the FV2200 software, raw data from all corresponding SSPs were combined.

In addition, ESU-wide PAI_{CanEye} was determined from DHPs by applying the CAN-EYE V6.313 software (INRA EmmaH, 2014). DHPs were captured with a Nikon D300s (resolution: 4288 × 2848 pixels) and Nikon D5100 (resolution: 4928 × 3264 pixels) equipped with an AF DX FISHEYE-NIKKOR (10.5 mm 1 : 2.8 G ED). The height of the camera including the lens is about 12 cm. Following Weiss et al. (2004), 10 DHPs per ESU (2 per SSP) were acquired in nadir and zenith view when plant heights were ≤ 25 and > 25 cm, respectively. DHPs were taken at a distance of approximately 1 m from the ESU diagonal to prevent an influence of the disturbed canopy architecture. For upward acquisitions, the camera was placed on the ground between neighboring planting rows to preserve the canopy structure. On potato fields, photos were taken in the middle of neighboring plants on top of the ridge and from the bottom of the furrow, respectively. Downward photos were generally acquired 0.3 m above the top of canopy.

DHPs were pre-processed using the “rtiff” R software package (Kort, 2014). For upward photos, the “intensity-mean” (Xu et al., 2004) of each pixel was calculated. Pixels were assigned to the classes “vegetation” and “sky” by applying the Ridler clustering method (Ridler and Calvard, 1978) to the intensity-mean layer as recommended by Jonckheere et al. (2005). If significant misclassification occurred due to low brightness differences between sunlit vegetation and blue sky, the Ridler clustering was applied to the “excess blue-ness” layer (Xu et al., 2004). Downward photos were binarized according to the classes “vegetation” and “soil” by employing the classification algorithm described in Sect. 4.1.2 without distinguishing between green and senescent vegetation.

Classification artifacts resulting from perturbing objects (e.g., legs of the photographer) and overexposed parts in the DHPs were masked out manually with the KolourPaint software (version 4.14.1; KDE, 2013) that permits lossless storage of binary files in tagged image file (TIF) format. Afterwards, circular areas of interest were extracted with a radius equal to the minimal distance between the optical center (Baret, 2004) and the border of the image. The circular area of interest corresponds to a view angle of 42.5 and 37.5° for the upward and downward photos, respectively. Files were imported into the CAN-EYE V6.313 software (INRA EmmaH, 2014) and the “true” PAI (PAI_{CanEye}) of each ESU was calculated with the CAN-EYE V5.1 formula (Weiss and Baret, 2014).

Starting in June 2013, at least one of the two methods was employed on each day of field work. The methods were employed alternatively, but depending on the crop type, between 16 and 61 pairs of values from simultaneous measurements are available (Table 3). PAI_{LAI2200} and PAI_{CanEye} values were found to differ by up to 5.97 with a median deviation of 2.17. Thus, species-specific linear calibration functions (Eq. 2) were set up to establish consistent and comparable time series of ESU-wide PAI (PAI_{estLAI2200}) values:

$$ \text{PAI}_{\text{estLAI2200}} = m \cdot \text{PAI}_{\text{CanEye}} + n. $$

(2)

Coefficients $m$ and $n$ were derived from pairs of values of PAI_{CanEye} and PAI_{LAI2200}. The determined coefficients are shown in Table 3 and are supplemented by the Pearson coefficient of determination ($R^2$), the root mean square error (RMSE) of predicted PAI_{estLAI2200} and measured PAI_{LAI2200}, the calibration ranges, and the number of utilized pairs $N$.

### 4.1.4 Awn length and ear inclination

Besides leaves, ears influence the canopy reflectance of cereals. The contribution of ears varies with the awn length...
At 52°, moved, stored in a plastic bag for transport, and oven-dried in a surface square area of 1 m around SSP12 were re-

located in a 1 m circuit of each SSP. Complementary mode, minimum, and maximum ear inclination was estimated once per ESU, in 2014. Angles of 0 and 180° correspond to a vertical ear with the top up and down, respectively.

4.1.5 Above-ground biomass and yield

Above-ground biomass (AGB) has been used previously as an indicator of the density of plant compartments that can interact with radiation (e.g., Park and Deering, 1982). Moreover, AGB is an essential parameter for synthetic aperture radar (SAR) applications and is also useful for the prediction of crop yields (Mattia et al., 2003). In 2014, dry AGB was determined once per ESU, on average 10 days before harvesting. All above-ground plant compartments situated in a surface square area of 1 × 1 m around SSP12 were removed, stored in a plastic bag for transport, and oven-dried at 52°C until a constant weight was reached. Afterwards, the dry-weight biomass was determined. Moreover, data on fruit yields (Fr yield/acreage) in 2013 and 2014 were provided by Geratal Agrar for the acreages where ESUs were installed. In 2014, Geratal Agrar provided additional information on the harvested AGB (‘Biom above gr/acreage’) of winter wheat, i.e., fruit yield and straw, that was cultivated on acreage 430.

4.1.6 Phenology

Phenological development stages create a basis for the comparison of biophysical and biochemical parameters of crops growing under different climatic, soil, illumination, and management conditions (Hank et al., 2015). Phenological development (BBCHkey) on each ESU was documented in 2014 by applying the growing stage keys of the extended BBCH scale (Meier, 2001). The BBCHkey can range between 0 (i.e., dry seed) and 99 (i.e., harvested product), while specific numbers correspond to defined stages of the phenological evolution. For example, values between 60 and 69 refer to the principal growth state of flowering. In addition, crops were photographed with a Nikon D5000 in vertical and oblique view to enhance the documentation of phenological states. Photos feature a folding ruler for scale. The photog-

raphs from 2013 (https://doi.org/10.1594/PANGAEA.874698) and 2014 (https://doi.org/10.1594/PANGAEA.874699) can be downloaded from PANGAEA.

4.2 Leaf structural and biochemical parameters

4.2.1 Chlorophyll content

Leaf chlorophyll pigments absorb radiation in the blue and red domain and play an important role in the assessment of the physiological status of the vegetation and the quantification of the photosynthetic activity (Blackburn, 1998). Content of leaf chlorophyll a (Chl a) and b (Chl b), and the sum of chlorophyll a and b (Chl a + b), were derived from nondestructive absorbance measurements (ChlSPAD) with the SPAD-502Plus chlorophyll meter (Konica Minolta, Inc.). Within a circuit of 1 m around each SSP, 10 readings were taken following the instructions of Konica Minolta (2012). Since major parts of the canopy reflectance in the visible range result from the uppermost leaves (Monteith, 1969), 7 of 10 ChlSPAD readings were taken in the upper two-thirds of the plants. The remaining three measurements were taken from leaves located rather close to the ground.

The dimensionless ChlSPAD values were converted into chlorophyll contents (in µg cm⁻²) with crop type specific calibration functions (Table 4). For the set-up of these functions about 20 leaves were sampled for each investigated species in the field. Mean ChlSPAD values were determined from five ChlSPAD readings covering a circular area with a diameter of 7.3 mm. Afterwards, these leaf disks were punched out and transferred into Eppendorf tubes that were subsequently transported in a Dewar flask filled with liquid nitrogen. Samples were stored at −80°C in a freezer until lab analysis. Chlorophyll was extracted with a lab stirrer (RZR 2102 control, Heidolph Instruments GmbH & Co. KG) while adding 80 % buffered acetone (Porra and Grimme, 1974). After a minimum resting time of 15 min, cooled samples were centrifuged (10 min at 4°C; 16 100 rcf) and the extract decanted. The absorption of the extract was determined at 647, 664, and 750 nm with a UV-160A UV–Visible Recording Spectrophotometer (Shimadzu Corp.) and the chlorophyll content was calculated with the formula of Lichtenthaler and Buschmann (2001). Following Markwell et al. (1995), an exponential relationship (Eq. 3)

\[ Chl X = k \cdot e^{-ChlSPAD} \]

was assumed between ChlSPAD readings and chlorophyll contents Chl a, Chl b, and Chl a + b (in µg cm⁻²; represented by Chl X). Calibration coefficients k and l were determined separately for Chl a, Chl b, and Chl a + b (Table 4). Pearson’s coefficient of determination (R²) was used as a measure of goodness for the calibration equation.

Accuracy and precision of ChlSPAD readings were ensured by 30 measurements with a SPAD-502Plus reading checker (Konica Minolta, 2012) that were performed before and after the field working days. Biases range from −1.5 to 1.2, with a median of −0.1, which is below the tolerance of ±3.0 indicated by the manufacturer. The 1σ errors vary between 0.1 and 0.7, with a median of 0.1. The measurement precision of the spectrophotometer was ascertained by 75 periodically collected triplicate determinations. The triplicate determinations reveal chlorophyll contents with a median 1σ error on the order of 0.1 µg cm⁻² and reach maximum 1σ errors of 2.3, 1.1, and 3.4 µg cm⁻² for Chl a, Chl b, and Chl a + b, respectively.
### 4.2.2 Leaf dry matter and equivalent leaf water

Leaf dry matter (Leaf dry mat) and equivalent leaf water (Leaf water) are variables of the PROSPECT-5 radiative transfer model (Féret et al., 2008) that is implemented in EO-LDAS. Leaf dry matter is an indicator of cellulose and lignin that absorb shortwave infrared radiation (Baret and Fourt, 1997). The equivalent leaf water exerts an influence on the optical path through the leaf and causes water absorption bands in the wavelength range from 1400 to 2500 nm (Allen et al., 1969). Leaf dry matter and equivalent leaf water were determined gravimetrically and based on image analysis in 2014. Leaves were collected representatively from the upper, middle, and lower parts of several plants next to SSP00. The leaves were unfurled on a rectangular reference panel (16 × 25.5 cm) and pressed flat with a transparent foil, and photos were taken to determine the leaf area (Area). Image analysis included the following steps: removal of artifacts (e.g., shadows, reflections), masking out of areas beyond the reference panel, binarization by assigning a value of 1 to pixels belonging to leaves and a value of 0 to the remaining pixels within the masked area, rectification of the image subset corresponding to the reference panel, extraction of the pixel statistics, and calculation of the leaf area. Image analysis was carried out with R software package “raster” (Hijmans, 2014) and ArcGIS (version 10.2; ESRI, 2013).

After the image acquisition, leaves were put in weighed sealable zip bags and transported to the laboratory. Fresh mass ($m_{\text{fresh}}$) was determined on the same day. Afterwards, samples were oven-dried at 52°C and dry mass ($m_{\text{dry}}$) was ascertained when constant weight was reached. Leaf dry matter (Leaf dry mat) and equivalent leaf water content (Leaf water) were calculated by applying Eqs. (4) and (5) (Baret and Fourt, 1997):

\[
\text{Leaf dry mat} = \frac{m_{\text{dry}}}{\text{Area}} \quad (4)
\]

and

\[
\text{Leaf water} = \frac{m_{\text{fresh}} - m_{\text{dry}}}{\text{Area} \cdot \rho_{\text{water}}}, \quad (5)
\]

where $\rho_{\text{water}}$ denotes the density of water, which was assumed to be 1 g cm$^{-3}$.

The precision of the Leaf dry mat and Leaf water measurements was examined based on at least two replicate determinations per investigated cultivar. The 1σ errors calculated from the triplicate determinations for Leaf dry mat and Leaf water were $\leq 6 \times 10^{-4}$ g cm$^{-2}$ and $\leq 21 \times 10^{-4}$ cm with associated median values of $1.7 \times 10^{-4}$ g cm$^{-2}$ and $3.5 \times 10^{-4}$ cm, respectively.

### 4.3 Soil moisture

In the visible to middle infrared range soil moisture influences the reflectance of the soil surface (Jacquemoud et al., 1992). The mean soil moisture in the uppermost 6 cm of the topsoil was ascertained in two different ways: (1) gravimetrically based on samples taken with volumetric sampling rings (100 cm$^2$) and (2) with a HH-2 moisture meter equipped with a ThetaProbe type ML2x (Delta-T Devices Ltd.). With both methods, measurements were carried out ~0.5 m from the ESU diagonal at a SSP in the middle of neighboring planting rows. A high small-scale soil moisture variability is to be expected on potato fields with high values on the furrow bottom and low values on the furrow ridge (Robinson, 1999). Thus, five measurements were performed per examined SSP: one in the middle of the furrow ridge centered between neighboring plants and two additional measurements on each side, i.e., one measurement in the middle of the slope and another one at the bottom of the furrow, respectively.

The gravimetric soil moisture was determined once per ESU on each field working day. At SSP12, a volumetric sampling ring was driven into the soil (five sampling rings on potato fields). Volumetric sampling rings were excavated and the samples were filled into sealable zip bags that were stored in a cooling bag during transport. Wet mass (Wet m) was determined on the same day. Afterwards, samples were oven-dried at 105°C until a constant weight was reached (Dry m). Gravimetric soil moisture was calculated relative to the wet mass ($\text{wetgrav}_{\text{SoilMoist}}$). Volumetric soil moisture...
Table 5. Coefficients $p_x$ and $q_x$ of the linear calibration functions (Eq. 6) for the conversion of the output voltage ($\text{Volt}_{\text{outp}}$, in mV) measured with the ML2x sensor into gravimetric soil moisture ($\text{est\_wetgrav\_SoilMoist}$, in wt\% relative to the wet mass) and volumetric soil moisture ($\text{est\_vol\_SoilMoist}$, in % vol), corresponding coefficients of determination (Pearson’s $R^2$) and root mean square errors (RMSEs), and the range and number $N$ of $\text{Volt}_{\text{outp}}$ values involved in the calibration procedure.

<table>
<thead>
<tr>
<th>Field</th>
<th>$\text{est_wetgrav_SoilMoist}$</th>
<th>$\text{est_vol_SoilMoist}$</th>
<th>$\text{Volt}_{\text{outp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_{\text{wetgrav}}$</td>
<td>$q_{\text{wetgrav}}$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>340</td>
<td>0.0002</td>
<td>0.0330</td>
<td>0.80</td>
</tr>
<tr>
<td>350</td>
<td>0.0003</td>
<td>0.0235</td>
<td>0.88</td>
</tr>
<tr>
<td>430</td>
<td>0.0002</td>
<td>0.0473</td>
<td>0.73</td>
</tr>
<tr>
<td>440</td>
<td>0.0218</td>
<td>3.7462</td>
<td>0.68</td>
</tr>
<tr>
<td>470</td>
<td>0.0310</td>
<td>−2.0428</td>
<td>0.82</td>
</tr>
<tr>
<td>500</td>
<td>0.0220</td>
<td>3.4372</td>
<td>0.78</td>
</tr>
<tr>
<td>771</td>
<td>0.0214</td>
<td>4.0063</td>
<td>0.71</td>
</tr>
<tr>
<td>820</td>
<td>0.0121</td>
<td>12.0360</td>
<td>0.38</td>
</tr>
<tr>
<td>830</td>
<td>0.0185</td>
<td>9.2332</td>
<td>0.64</td>
</tr>
</tbody>
</table>

(vol\_SoilMoist) and the dry bulk density (dBd) of the soil were calculated according to Hartge and Horn (2009). For all fields, a mean dBd of 1.3 g cm$^{-2}$ and a corresponding 95% confidence level of 0.1 g cm$^{-3}$ were obtained separately from all samples gathered in 2013 and 2014 (Table 5).

Measurements with the HH-2 moisture meter were carried out for each SSP. In 2013, one measurement was conducted per SPP, while in 2014, three measurements were carried out in order to quantify small-scale variability. On potato fields, five readings were taken at each SSP in both years. In the case that acquisitions in the vicinity of dry cracks could not be avoided (Delta-T Devices, 1999), the width of the dry cracks (W max) was determined. The occurrence of dry cracks implies a higher uncertainty of the measurements (Delta-T Devices, 1999). The ML2x sensor detects an output voltage ($\text{Volt}_{\text{outp}}$) which is subsequently transformed into gravimetric ($\text{est\_wetgrav\_SoilMoist}$) or volumetric soil moisture ($\text{est\_vol\_SoilMoist}$). The manufacturer suggests adjusting the (linear) calibration equations for the given soil type (Delta-T Devices, 1999). Hence, the sensor was calibrated separately for each field based on soil moisture values obtained from volumetric sampling rings. The following linear calibration functions (Eq. 6; Table 5) were fitted:

$$\text{est\_X\_SoilMoist} = p_X \cdot \text{Volt}_{\text{outp}} + q_X.$$  (6)

$X$ indicates the type of soil moisture (gravimetric or volumetric); i.e., the gain $p_X$ and the offset $q_X$ were determined separately for $\text{est\_wetgrav\_SoilMoist}$ and $\text{est\_vol\_SoilMoist}$.

The precision of soil moisture determinations was assessed based on multiple measurements ($N \geq 3$). The 1σ errors for $\text{wetgrav\_SoilMoist}$ and $\text{est\_wetgrav\_SoilMoist}$ range from 0.14 to 1.92 wt% and 0.03 to 7.26 wt% with medians amounting to 0.42 and 0.87 wt%, respectively. The 1σ errors for $\text{vol\_SoilMoist}$ and $\text{est\_vol\_SoilMoist}$ range from 0.25 to 3.52 % vol and 0.01 to 12.90 % vol, while the associated medians are 0.82 and 1.60 % vol, respectively.

4.4 Hyperspectral characteristic of plants and soil

Raw digital numbers (DNs) of the surface spectra and the related hemispheric-conical reflectance factors (Schaepman-Strub et al., 2006) were measured with a FieldSpec 3 spectroradiometer (FS3; Analytical Spectral Devices Inc.). Spectra were recorded in the wavelength ($\lambda$) range from 350 to 1000 nm and 1001 to 2500 nm with sampling intervals of 1.4 and 2 nm, respectively (ASD, 2005). Measurements were carried out 1 m above the top of canopy with an 8° field of view in the nadir direction. The fiber optic cable connected to the FS3 sensor was mounted on a 1.3 m long pole. Looking southward, the pole was held horizontally and moved 50° to the left and right, respectively, while 10 measurements were recorded. Readings were taken successively at all SSPs of an ESU accompanied by the acquisition of reference spectra immediately before and after the target measurements (Milton et al., 2009). The reference spectra were acquired from a Spectralon reference panel (SRT-99-050; Labsphere, Inc.) that was placed on plane-parallel dimensionally stable packing foam (absolute reflectance factors $r < 0.045$ for $\lambda \in [350 \text{ nm} \mid 2500 \text{ nm}]$). During the measurements, the foam was held above the top of canopy, while its horizontal leveling was controlled with a spirit level (T type) placed at the edge of the foam. The comparison of the reference spectra recorded before and after the target measurements gives an indication of the stability of the prevailing atmospheric conditions (ASD, 2005). A description of haze and clouds in the vicinity of the Sun during the hyperspectral measurements is part of the datasets provided at PANGAEA for 2013 (https://doi.org/10.1594/PANGAEA.874243) and 2014 (https://doi.org/10.1594/PANGAEA.874245). Measurements of atmospheric conditions supplement the data (see Sect. 4.5).

Hyperspectral raw data were pre-processed in five steps:
1. extraction of the acquisition time from the metadata for each hyperspectral measurement;

2. linear interpolation of the DNs acquired over the Spectralon before and after the target measurement runs to get an estimate of the white reference (WR) spectra at the time (t) of each target measurement (Milton et al., 2009). Based on the estimated digital numbers of the white reference (DN\textsubscript{estWR}), target digital numbers (DN\textsubscript{target}) were converted into relative reflectance factors \( r_{rel} \) by applying Eq. (7) (Peddle et al., 2001):

\[
r_{rel}(\lambda, t) = \frac{DN_{target}(\lambda, t)}{DN_{estWR}(\lambda, t)},
\]

3. correction of the reflectance factor offset occurring between the FS3 sensors VNIR (350–1000 nm) and SWIR1 (1001–1800 nm) by an adjustment of the relative reflectance factors in VNIR (\( r_{rel,\text{VNIR}} \)) to the level of SWIR1 relative reflectance factors with Eq. (8):

\[
r_{rel,\text{VNIRcorr}}(\lambda) = r_{rel,\text{VNIR}}(\lambda) + r_{rel}(\lambda = 1001\text{ nm}) - r_{rel}(\lambda = 1000\text{ nm}).
\]

Relative reflectance factors recorded in the SWIR1 domain were selected as a reference level since the SWIR1 detector shows the smallest temperature-related spectral drift (Hueni and Bialek, 2017);

4. transformation of \( r_{rel} \) into absolute reflectance factors \( r \) by multiplication by the reflectance of the Spectralon reference panel (Schaepman-Strub et al., 2006);

5. masking out of reflectance factors in wavelength ranges that were affected by water absorption (\( \lambda = 1350 \) to 1460 nm, \( \lambda = 1790 \) to 1960 nm; Robinson and MacArthur, 2011) and strong noise (\( \lambda = 2400 \) to 2500 nm). Pre-processing was carried out in the R software environment by applying the “prospectr” package (Stevens and Ramirez-Lopez, 2013).

4.5 Meteorological data and sky conditions

Data on air temperature, humidity, wind direction, and diffuse solar radiation, among others, were gathered at the Gebesee Fluxnet site (ID: DE-Geb; MPI BGC, 2015). Data access is provided via the European Fluxes Database Cluster (http://gaia.agraria.unitus.it/home). Furthermore, meteorological and climate data (e.g., air temperature, relative humidity, air pressure, precipitation, cloud coverage, wind speed) accompanied by phenological data are recorded at the Duchwig Deutscher Wetterdienst (DWD) station (Fig. 1; station ID: 896; DWD, 2016) that is located about 4 km west of the Gebesee test site. These data are available via the WebWerdis web portal (https://werdis.dwd.de). Additional data on selected atmospheric and meteorological parameters were collected during the field campaign.

4.5.1 Solar irradiance, aerosol optical thickness, and column water vapor

Aerosol optical thickness (AOT) and column water vapor (CWV) characterize the state of the atmosphere and are utilized to correct, for example, influences of aerosol scattering or water absorption on satellite images (Richter and Schläpfer, 2016). In 2014, direct solar irradiance (\( E \)), aerosol optical thickness, and column water vapor were derived from measurements with a MICROTOPS II Sun photometer (model 540; Solar Light Co., Inc.) at wavelengths of 340±0.3, 440±1.5, 675±1.5, 870±1.5, and 936±1.5 nm, respectively (Solar Light, 2007). Additionally, the acquisition time, air mass (Optical airm.), and Sun zenith angle (SZA) were recorded. The Sun photometer was operated using the manufacturer’s calibration constants delivered with the instrument in January 2014. The quartz window in front of the sensors was cleaned before each field measurement day to avoid measurement errors (Ichoku et al., 2002) and the Sun photometer was mounted on a tripod to enable accurate pointing to the Sun (Morris et al., 2001). One reading per ESU was taken, either at SSP00 or at SSP24. All measurements were annotated with descriptions of haze and cloud cover.

4.5.2 Sky conditions

Cloud cover and photos of the sky condition are indicators of the prevailing illumination conditions and thus relevant metadata for the hyperspectral data acquired with the FieldSpec 3 spectroradiometer (Pfitzner et al., 2006). Overall cloud coverage (Cloud cov) expressed in oktas was assessed visually and documented once per ESU. In addition, photos were taken at SSP00 to depict the condition of the sky around the zenith and close to the horizon in the direction of SSP24 (i.e., NNE). The photos acquired in 2013 (https://doi.org/10.1594/PANGAEA.874250) and 2014 (https://doi.org/10.1594/PANGAEA.874697) can be accessed at PANGAEA. Descriptions of the haze and cloud cover close to the Sun during the spectrometer (Sect. 4.4) and Sun photometer (Sect. 4.5.1) measurements were added as an annotation to the corresponding parameters.

4.6 Further investigations

4.6.1 Landscape photos

Landscape photos were taken at SSP00 oriented parallel and orthogonal to the direction of the planting rows and toward SSP24, respectively. The photos depict the condition of the vegetation on the ESU and its surroundings and are available at PANGAEA for 2013 (https://doi.org/10.1594/PANGAEA.874700) and 2014 (https://doi.org/10.1594/PANGAEA.874703).
Comparison between space-borne and ground reference data requires a solid foundation for the geo-referencing of satellite images. Thus, coordinates and heights above the ellipsoid (HAE) were recorded at SSP00 and SSP24 of all ESUs using differential global navigation satellite systems (dGNSS). In addition, 15 ground control points (GCPs) and 20 checkpoints (CPs) in the vicinity of the Gebesee test site were surveyed. GCPs were selected in accordance with the guidelines of Kapnias et al. (2008) and considering the requirements of PCI Geomatics (2009) for the orthorectification of satellite images with the rational functions math model. CPs were placed between the GCPs, following the recommendations of Kapnias et al. (2008). All points were located on straight road segments, most of them on road junctions. Supporting information for the localization of survey points in satellite images (e.g., the width of the roads) and photos showing the setting of the GCPs is provided at PANGAEA (https://doi.org/10.1594/PANGAEA.874247).

GCPs and positions of ESUs investigated in 2013 were surveyed with a LEICA GS15 rover. Measurements at each survey point were integrated over 2 min to obtain mean values from 120 position readings (2 readings per second). Data post-processing was carried out with the Leica Geo Office 8.3 software (LEICA Geosystems, 2012). A virtual reference station (VRS; 51°05′N, 10°56′E) was generated based on the SAPOS Thuringia network of continuously operating GNSS base stations (AdV, 2013). The differential calculation of the coordinates referred to this VRS, with a maximum distance between survey points and VRS of 8.1 km.

CPs and ESUs investigated in 2014 were surveyed with a STONEX S9IIIN rover which was operated in real-time kinematic (RTK) mode connected to the SAPOS base stations. The maximum distance between survey points and the nearest SAPOS base station (reference station Erfurt; TLVermGeo, 2016) was 15.4 km. The mean positional precision (1σ error) in the horizontal direction (2-D) is < 0.01 m in 2013 and 0.01 m in 2014, respectively. In 2014, repeated triplicate position determinations were carried out on different days for most of the survey points to allow for an estimation of uncertainties introduced by the placement of the rover and changing satellite constellations. The resulting 1σ error is ≤ 0.05 and ≤ 0.03 m in the horizontal and vertical directions, respectively.

HAEs were transformed into physical heights (Altitude) referring to the German state height reference system (DHHN92) based on bi-cubic spline interpolation between data points provided with the German Combined QuasiGeoid 2011 grid (GCC2011; BKG, 2011). GCC2011 data and the software for the interpolation (gintbs.exe) and conversion (geoid.exe) were kindly provided by the Federal Agency for Cartography and Geodesy (BKG).

5 Results
5.1 Synchronization of in situ measurements and satellite acquisitions

Archival accessible via USGS Earth Explorer, ESA EOLi, and RESA EyeFind host 11 satellite images of the Gebesee test site with zero or low (< 25 %) cloud coverage that were acquired by the sensors of Landsat-7, -8, SPOT 5, and Rapid-Eye in 2013. For 10 of these acquisitions, in situ data were collected less than 1 day apart. In seven cases ground reference data were gathered on the same day (Fig. 3). Among the 11 satellite images, 7 are cloud free, while certain ESUs are covered by haze and clouds on the remaining images. For 2014, 21 satellite images are available showing the Gebesee test site with zero or low cloud coverage. The number of satellite images acquired no more than 1 day before or after the collection of the in situ data is 15. In total, seven of the images were acquired on a day of field work (Fig. 3). Moreover, 11 of the 21 images are cloud free.

5.2 Interannual and spatial variability

Meteorological conditions at the Gebesee test site differed considerably between 2013 and 2014. This becomes apparent in the evolution of the investigated parameters. In Fig. 4, time series of soil moisture, plant height, and proportion of senescent material on ESUs cultivated with spring wheat cultivar Taifun are compared with mean monthly temperature and monthly rainfall. Compared to mean values of long-term time series recorded at the Dachwig DWD station (1991–2014), the beginning of the year 2013 was characterized by abnormally long-lasting low temperatures (Fig. 4a). Only starting from 9 April did the daily mean air temperature persistently exceed the mean daily temperature of 3.5 °C required for sowing and emergence of wheat (Porter and Gawith, 1999; DWD, 2015). On the same day, spring wheat was drilled on acreage 430 and 1 day later on acreage 830. In contrast, spring wheat was drilled on 13 February on acreage 350 in 2014, when the temperature was already sufficiently high. Mean temperatures from February to April 2014 range among the highest values measured between 1991 and 2014 (Fig. 4c). Synchronously, the emergence of inflorescence (BBCHkey: 59) was completed on 19 and 26 June 2013 and 1 June 2014 at ESU 430-2, 830-3, and 350-1, respectively.

The first half of 2014, except May, was characterized by monthly precipitations close to the long-term minimum (Fig. 4a). Until June, monthly precipitation was higher in 2013 compared to 2014 and entails a higher soil moisture content in 2013 (Fig. 4b). Increasing temperature which causes rising evapotranspiration rates in combination with
low precipitation led to an early decrease in the soil moisture content in 2014 (Fig. 4a, b). Senescence appeared about 1 month earlier in 2014 compared to 2013 (Fig. 4d). In 2014, progressing senescence and the last (slower) phase of plant growth coincided, while plants were still green during this phase in 2013 (Fig. 4c, d). The slow growing phase lasted 1 week in 2013 until maximum plant height was reached, while it took 3 weeks in 2014 (Fig. 4c). After greenness was gone, ears started to droop, which led to a decrease in plant height (Fig. 4c, d). This decrease indicated finalization of ear ripening (BBCH principal growing stage: 9) and appeared 3 weeks later in 2013 compared to 2014. High monthly precipitation in July and August 2014 delayed the harvest until 2 August. Compared to the harvest in 2013 on acreages 430 and 830, it took place only 10 and 13 days in advance, respectively.

Spatial variability is, for example, documented in the evolution of parameters characterizing the growth of spring wheat on acreage 430 and 830 in 2013. Soil moisture content on ESU 430-2 is 2 to 8 wt% lower than on ESU 830-3 (Fig. 4b). Nevertheless, plants on ESU 430-2 grow faster and reach a mean maximum plant height that is 0.1 m higher than on ESU 830-3 (Fig. 4c). On both ESUs senescence starts synchronously, but greenness vanishes about 1 week earlier at ESU 830-3 (Fig. 4d). Due to the proximity of the acreages meteorological conditions can be assumed identical. Instead, the observed differences might be partially attributable to varying soil fertility. This can be explained by artificial manure, but may be also due to differing soil types. Acreage 430 is characterized by rather fertile Haplic Chernozems promoting plant growth (Zech et al., 2014), while acreage 830 is characterized by Vertic Chernozems with an elevated clay content that confines the amount of plant-available soil water and may lead to an earlier senescence (Blume et al., 2016). However, the data indicate that interannual variability caused larger differences with respect to the investigated parameters than prevailing heterogeneity in pedological conditions (Fig. 4b–d).

5.3 Influence of vegetation parameters on hyperspectral reflectance factors and their variability between crop types

The simultaneous acquisition of in situ data and hyperspectral measurements permits the examination of relationships between plant physiological states and the surface reflectance factors that are expected to vary between different phenological stages and crop types (e.g., Haboudane et al., 2004). This is exemplified for winter rape, winter wheat, and potato that belong to the plagiophile, erectophile, and planophile leaf angle distribution (LAD) classes defined by de Wit (1965) and Eagelson (2004), respectively, and are representatives of all LAD classes sampled during the field campaigns.

Figure 5 shows nadir photos as well as mean values with 95% confidence intervals of selected vegetation parameters.
and absolute reflectance factors $r$ from which the MERIS Terrestrial Chlorophyll Index (MTCI) following Dash and Curran (2004) was calculated (Eq. 9).

$$\text{MTCI} = \frac{r(\lambda = 754 \text{ nm}) - r(\lambda = 709 \text{ nm})}{r(\lambda = 709 \text{ nm}) - r(\lambda = 681 \text{ nm})}$$

(9)

The data characterize the three crop types in a comparable phenological state, i.e., at the end of the flowering stage in 2014. Winter rape already reached the stage of declining flowering ($BBCH_{key}$: 65–67) on 30 April 2014, while the end of flowering of winter wheat ($BBCH_{key}$: 69) and potato ($BBCH_{key}$: 69–70) was only observed on 6 June and 4 July 2014, respectively.

The FVC that was derived from nadir photos (Fig. 5a, b) is $97 \pm 1$, $75 \pm 1$, and $92 \pm 1 \%$ for winter rape, winter wheat, and potato, respectively, with the proportion of senescent material (PSM) being $< 5 \%$ for all three crop types. The highest mean $\text{PAI}_{LAI_{2200}}$ (Fig. 5c) was determined for winter rape and amounts to $6.0 \pm 0.3$. The mean $\text{PAI}_{LAI_{2200}}$ of winter wheat ($5.5 \pm 0.4$) is higher than for potato ($4.0 \pm 0.4$), despite the lower FVC. Similarly, $\text{Chl a} + \text{b}$ (Fig. 5d) is highest for winter rape ($64 \pm 5 \mu \text{g cm}^{-2}$), followed by winter wheat ($53 \pm 7 \mu \text{g cm}^{-2}$) and potato ($48 \pm 4 \mu \text{g cm}^{-2}$).

The corresponding absolute canopy reflectance factors (350–2400 nm; Fig. 5e) of winter rape and potato are rather similar, with a mean deviation of 0.037. The absolute reflectance factors of winter wheat are generally lower and deviate by 0.076 and 0.071 on average from the absolute reflectance factors of winter rape and potato, respectively. Notably, illumination conditions were similar during the acquisition of the hyperspectral data, with SZAs ranging from 44 to 46°. Hence, correction for illumination conditions is ex-
pendable in this example. Figure 5f depicts the MTCI that is expected to increase linearly with increasing Chl a + b (Liang et al., 2016). However, the MTCI for winter rape (3.0 ± 0.3) is lower than for winter wheat (7.4 ± 0.3) and potato (3.5 ± 0.01), which is in contrast to the Chl a + b values.

The lower FVC of winter wheat as compared to potato (Fig. 5b) which seems counterintuitive given the higher mean PAI_{A2200} (Fig. 5c) can be explained by differing LADs (Weiss et al., 2004). At the end of the flowering stage the leaf development and stem elongation of winter rape, winter wheat, and potato are completed (Meier, 2001). The crops cover the space between the planting rows and the FVC is close to the species-specific maximum value. The canopy of winter wheat is mainly characterized by vertically oriented leaves (erectophile LAD). From the nadir perspective, only a small proportion of the leaf area contributes to the coverage of the soil. In contrast, potato leaves are almost horizontally oriented (planophile LAD), which leads to a large coverage despite a smaller leaf area. PAI and LAD exert influence on the leaf area that interacts with solar radiation and, thus, the reflectance factors in the wavelength range from 400 to 2500 nm (Mousivand et al., 2014). Therefore, the combination of PAI and LAD might explain the lower absolute reflectance factors of winter wheat as compared to winter rape and potato (Fig. 5e).

In the wavelength range from 400 to 700 nm the absorption of blue and red light increases proportionally with Chl a + b (Lichtenhalter and Buschmann, 2001). Considering measured Chl a + b, the highest absorption would be expected for winter rape, but the leaves are partially covered by yellow petals. In addition, these petals increase the reflectance factors between 500 and 2500 nm (Mousivand et al., 2014). Therefore, the combination of PAI and LAD might explain the lower absolute reflectance factors of winter wheat as compared to winter rape and potato (Fig. 5e).

The current example illustrates that the database can be used to link changes in spectral characteristics over the cultivation period to processes that are manifested in vegetation parameters. Interrelations between the absolute surface reflectance factors and vegetation parameters can be assessed for various crop types with differing canopy architectures. Therefore, the database can contribute to the development, validation, and enhancement of empirical and process-based models for the derivation of plant physiological states of crops.

6 Data availability

The database described in this paper is archived at PANGAEA (https://doi.org/10.1594/PANGAEA.874251, Truckenbrodt and Baade, 2017) and comprises 13 datasets. An overview of all available parameters, hyperlinks to the corresponding datasets, and a short parameter characterization are provided in the file “Description of investigated parameters”. Metadata on the investigated fields and crop types are summarized in the file “Metadata on the cultivars and investigated fields” that supplements the database.

7 Conclusions

This paper introduces a comprehensive and freely available ground reference database on the phenological evolution of seven crop types cultivated on the Gebesee test site in 2013 and 2014. A detailed description of the measurement design and data acquisition is provided. The uniqueness of the database is the high number of investigated vegetation parameters that influence the surface reflectance in the visible and infrared range and their simultaneous assessment for crops with various canopy architectures in conjunction with the high temporal resolution of the data acquisition. The land surface was investigated regarding soil moisture, biophysical plant parameters, and leaf structural and biochemical parameters. Data collection was accompanied by hyperspectral measurements of surface reflectance factors and characterization of atmospheric states. Ground reference and spaceborne data (RapidEye, SPOT 5, Landsat-7 and -8) acquired less than 1 day apart and with ≤25% of the test site being cloud covered are available for 10 and 15 days in 2013 and 2014, respectively.

The database provides, in general, a solid foundation for the set-up, validation, and enhancement of empirically and physically based models and remote sensing applications targeting crop monitoring. Parameters and spectral properties of various crop types can be compared by considering variations in space and time. Spatial variability is documented on the scale of SSFs and ESUs, and for selected crops within and between acreages. Interannual variability arises from distinct meteorological conditions in 2013 and 2014. The Gebesee test site is particularly suited for the acquisition of ground reference data. It is representative of cultivated areas in the mid-latitudes of central Europe. Due to its low relief energy (slope inclination <5%) and comparably large acreages (8.57 to 60.49 ha) it is convenient for the validation of remote sensing products. Since 1991 temperature, relative humidity, air pressure, cloud coverage, and wind speed have been recorded at the Dachwig DWD station, while rainfall records extend back to the 1960s (DWD, 2016). Combining the current database with ongoing measurements of CO2 and water vapor exchange at the Gebesee flux tower that started in 2001 (MPI BGC, 2015) opens up opportunities to test and validate soil–vegetation–atmosphere transfer (SVAT), surface-
energy-balance (SEB) models, and satellite-aided retrieval models. The database will be used to implement realistic prior information in EO-LDAS and to assess the effects on the accuracy of derived vegetation parameter values.
Appendix A: Alphabetical list of acronyms used in this study

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACF</td>
<td>apparent clumping factor</td>
</tr>
<tr>
<td>AGB</td>
<td>above-ground biomass</td>
</tr>
<tr>
<td>AgriSAR 2006</td>
<td>a ground and airborne campaign carried out on the DEMMIN test site, Germany, in 2006</td>
</tr>
<tr>
<td>AgriSAR 2009</td>
<td>a ground and airborne campaign carried out on the Barrax test site, Spain, in Flevoland, the Netherlands, and in Indian Head, Canada, in 2009</td>
</tr>
<tr>
<td>AOT</td>
<td>aerosol optical thickness</td>
</tr>
<tr>
<td>AquiferEx</td>
<td>field campaign of the Aquifer project (carried out in southern Tunisia in 2005)</td>
</tr>
<tr>
<td>Area</td>
<td>area of leaves sampled for the determination of Leaf dry mat and Leaf water</td>
</tr>
<tr>
<td>Awn l</td>
<td>awn length</td>
</tr>
<tr>
<td>BBCH</td>
<td>Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie</td>
</tr>
<tr>
<td>BBCHkey</td>
<td>growing stage key according to the extended BBCH scale</td>
</tr>
<tr>
<td>BigFoot</td>
<td>ground validation project conducted in North and South America to provide data on multiple scales for the MODIS Land Discipline Group from 2000 to 2003</td>
</tr>
<tr>
<td>Biom</td>
<td>harvested AGB (data provided by Geratal Agrar)</td>
</tr>
<tr>
<td>BKG</td>
<td>Bundesamt für Kartographie und Geodäsi (Federal Agency for Cartography and Geodesy, Germany)</td>
</tr>
<tr>
<td>CEFLES2</td>
<td>CarboEurope FLEX (Fluorescence Explorer) Sentinel-2 (a ground and airborne campaign carried out in southwest France in 2007)</td>
</tr>
<tr>
<td>Chl a</td>
<td>content of leaf chlorophyll a</td>
</tr>
<tr>
<td>Chl a + b</td>
<td>content of leaf chlorophyll a and b</td>
</tr>
<tr>
<td>Chl b</td>
<td>content of leaf chlorophyll b</td>
</tr>
<tr>
<td>Chl X</td>
<td>representation for Chl a, Chl b or Chl a + b (X can be a, b or a + b; see Eq. 3)</td>
</tr>
<tr>
<td>ChlSPAD</td>
<td>relative amount of leaf chlorophyll determined with the SPAD502Plus</td>
</tr>
<tr>
<td>Cloud cov</td>
<td>overall cloud coverage</td>
</tr>
<tr>
<td>CP</td>
<td>checkpoint</td>
</tr>
<tr>
<td>CWV</td>
<td>column water vapor</td>
</tr>
<tr>
<td>dBD</td>
<td>dry bulk density</td>
</tr>
<tr>
<td>dGNSS</td>
<td>differential Global Navigation Satellite System</td>
</tr>
<tr>
<td>DHHN92</td>
<td>Deutsches Haupthöhennetz 1992 (German state height reference system)</td>
</tr>
<tr>
<td>DHP</td>
<td>digital hemispherical photo</td>
</tr>
<tr>
<td>DN</td>
<td>digital number</td>
</tr>
<tr>
<td>DN_{estWR}</td>
<td>estimated digital numbers of the white reference</td>
</tr>
<tr>
<td>DN_{target}</td>
<td>digital numbers of the target</td>
</tr>
<tr>
<td>Dry m</td>
<td>Dry mass of soil sample</td>
</tr>
<tr>
<td>DWD</td>
<td>Deutscher Wetterdienst</td>
</tr>
<tr>
<td>E</td>
<td>direct solar irradiance</td>
</tr>
<tr>
<td>EnMAP</td>
<td>German Environmental Mapping and Analysis Program (a ground and hyperspectral airborne campaign carried out on different test sites in Germany from 2009 to 2015)</td>
</tr>
<tr>
<td>EO-LDAS</td>
<td>Earth Observation Land Data Assimilation System</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observing System</td>
</tr>
<tr>
<td>ESA EOli</td>
<td>European Space Agency Earth Observation Link</td>
</tr>
<tr>
<td>est_vol_SoilMoist</td>
<td>estimated vol_SoilMoist, i.e., the linear transformed Volt_outp</td>
</tr>
<tr>
<td>est_wetgrav_SoilMoist</td>
<td>estimated wetgrav_SoilMoist, i.e., the linear transformed Volt_outp</td>
</tr>
<tr>
<td>est_X_SoilMoist</td>
<td>representation for est_wetgrav_SoilMoist and est_vol_SoilMoist</td>
</tr>
<tr>
<td>(X can be gravimetric or volumetric; see Eq. 6)</td>
<td></td>
</tr>
<tr>
<td>ESU</td>
<td>elementary sampling unit</td>
</tr>
<tr>
<td>ETM +</td>
<td>Enhanced Thematic Mapper Plus (sensor carried by Landsat-7)</td>
</tr>
</tbody>
</table>
FoS fraction of sky
FOV field of view
Fr yield/acreage fruit yields (data provided by Geratal Agrar)
FS3 FieldSpec 3 spectroradiometer
FVC fractional vegetation cover
GCG2011 German Combined QuasiGeoid 2011
GCP ground control point
Geratal Agrar Geratal Agrar GmbH & Co. KG Andisleben
GNSS Global Navigation Satellite System
H hue
HAE height above ellipsoid
HRG High Resolution Geometric (sensor carried by SPOT 5)
HSL hue, saturation, lightness (color space)
HYFLEX HYperspectral FLuorescence EXperiment (a ground and hyperspectral airborne campaign carried out in the Ruhr catchment, Germany, in 2012)
Incl ear inclination
JECAM Joint Experiment of Crop Assessment and Monitoring
k ordinate intercept of the exponential function applied to determine Chl X (see Eq. 3)
L lightness
l relative rate of change of the exponential function applied to determine Chl X (see Eq. 3)
LAD leaf angle distribution
LAI leaf area index
LAI-2200 LAI-2200 Plant Canopy Analyzer (LI-COR Biosciences, Inc.)
Leaf dry mat leaf dry matter
Leaf water equivalent leaf water
LS7 Landsat-7 ETM+
LS8 Landsat-8 OLI
m slope of the linear function applied to determine PAIestLAI2000 (see Eq. 2)
max maximum of calibration range
m_dry dry mass of leaves sampled for the determination of Leaf dry mat and Leaf water
m_fresh fresh mass of leaves sampled for the determination of Leaf dry mat and Leaf water
min minimum of calibration range
MTCI Medium Resolution Imaging Spectrometer (MERIS) Terrestrial Chlorophyll Index
n ordinate intercept of the linear function applied to determine PAIestLAI2000 (see Eq. 2)
NASA National Aeronautics and Space Administration
nClassX number of pixels ascribed to class X by means of an automatic classification
\( X = \text{FVC} \) represents “vegetation” and \( X = \text{PSM} \) represents “senescent vegetation”
nRef_all number of pixels involved in the validation of the classification of “vegetation” and “senescent vegetation”
nRef_X number of pixels ascribed to class X by means of a visual inspection
\( X = \text{FVC} \) represents “vegetation” and \( X = \text{PSM} \) represents “senescent vegetation”
OLI Operational Land Imager (sensor carried by Landsat-8)
Optical airm air mass
PAI plant area index
PAI$_{\text{CanEye}}$ “true” PAI determined from DHPs with the CAN-EYE V6.313 software
PAI$_{\text{estLAI2000}}$ estimated PAI$_{\text{LAI2000}}$, i.e., the linear transformed PAI$_{\text{CanEye}}$ (see Eq. 2)
PAI$_{\text{LAI2000}}$ “true” PAI measured with LAI-2000
Plant h plant height
PSM proportion of senescent material
p$_{\text{vol}}$ gain, i.e., the slope of the linear function applied to determine est$_{\text{vol SoilMoist}}$ (see Eq. 6)
p$_{\text{wetgrav}}$ gain, i.e., the slope of the linear function applied to determine est$_{\text{wetgrav SoilMoist}}$ (see Eq. 6)
p$_{X}$ gain, i.e., the slope of the linear function applied to determine est$_{X \text{ SoilMoist}}$ (see Eq. 6)
offset, i.e., the ordinate intercept of the linear function applied to determine 
est_vol_{SoilMoist} \text{(see Eq. 6)}$

$q_{\text{wetgrav}}$
offset, i.e., the ordinate intercept of the linear function applied to determine 
est_{\text{wetgrav}}_{\text{SoilMoist}} \text{(see Eq. 6)}$

$q_X$
offset, i.e., the ordinate intercept of the linear function applied to determine 
est_X_{\text{SoilMoist}} \text{(see Eq. 6)}$

$r$
absolute reflectance factors

RE
RapidEye REIS

REIS
RapidEye Earth Imaging System (sensor carried by RapidEye)

RESA
RapidEye Science Archive

RGB
red, green, blue (color space)

RMSE
root mean square error

$r_{\text{rel}}$
relative reflectance factors

$r_{\text{rel}}_{\text{VNIR}}$
$r_{\text{rel}}$ in the VNIR

$r_{\text{rel}}_{\text{VNIRcorr}}$
$r_{\text{rel}}_{\text{VNIR}}$ adjusted to the level of $r_{\text{rel}}$ in the SWIR1

RTK
real-time kinematic

SAPOS
Satellitenpositionierungsdienst (Satellite Positioning Service; permanently operating GNSS stations in Germany)

SAR
synthetic aperture radar

SE PAI\text{LAI2000}
standard error of PAI\text{LAI2000}

SE Tilt
standard error of Tilt

SEB
surface-energy-balance model

SEN2FLEX
SEUtilne-2 and FLuorescence EXperiment (a ground and airborne campaign carried out on the Barrax test site, Spain, in 2005)

SEN3EXP
SEUtilne-3 EXPerimental Campaign (a ground, airborne and satellite campaign carried out on the Barrax test site, Spain, and in San Rossore, Italy, in 2009)

SPARC
Spectra bARrax Campaign (a remote sensing ground validation experiment on the Barrax test site, Spain, carried out in 2003 and 2004)

SPOT5
SPOT 5 HRG

SSP
secondary sampling point; each ESU consists of five SSPs named SSP00, SSP08, SSP12, SSP16, and SSP24

SVAT
soil–vegetation–atmosphere transfer model

SWIR1
shortwave infrared 1 range (1001–1800 nm)

SZA
Sun zenith angle

$t$
time

TIF
tagged image file

$Tilt$
mean foliage tilt angle

USGS
United States Geological Survey

UTM 32U
Universal Transverse Mercator coordinate system zone 32U

UV
ultraviolet

VNIR
visible and near-infrared range (350–1000 nm)

$vol_{\text{SoilMoist}}$
volumetric soil moisture (relative to the bulk volume)

$Volt_{\text{outp}}$
output voltage measured with the ML2x sensor

VRS
virtual reference station

$W_{\text{max}}$
maximum width of dry cracks

$Wet_m$
wet mass of soil sample

$wetgrav_{\text{SoilMoist}}$
gravimetric soil moisture (relative to the wet mass)

WR
white reference

$X_{\text{bias}}$
bias of the class $X$ derived from automatic pixel classification compared to class $X$ assigned by visual inspection ($X = \text{FVC}$ represents “vegetation” and $X = \text{PSM}$ represents “senescent vegetation”; see Eq. 1)

$\lambda$
wavelength

$\rho_{\text{water}}$
density of water
Author contributions. ST set up the experimental design of the field campaigns. She was in charge of the accomplishment of field work and the maintenance of the equipment. Moreover, she was involved in all field work and is responsible for the data processing. CS played a supervisory role and contributed to the development of the field campaign design.

The manuscript was written by ST with contributions from CS.

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References


JECAM (Joint Experiment for Crop Assessment and Monitoring): Joint Experiment for Crop Assessment and Monitoring, JECAM Annual Reports, available at: http://www.jecam.org/?/charter/annual-reports, last access: 3 December 2015.


TLL (Thüringer Landesanstalt für Landwirtschaft): Anpassung der Thüringer Landwirtschaft an den Klimawandel, Thüringer Ministerium für Landwirtschaft, Naturschutz und Umwelt, Jena, Germany, 12 pp., 2009.


TLUG (Thüringer Landesamt für Umwelt und Geologie): Bodenkarte von Thüringen 1 : 50 000, Blatt L 4930, TLUG, Jena, Germany, 2002.

TLVA (Thüringer Landesvermessungsamt): Topographische Karte 1 : 10 000, Blatt 4831-SW, TLVA, Erfurt, Germany, 2003.


