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Accuracy assessment on the number of flux terms needed to estimate in situ fAPAR

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ABSTRACT

The fraction of Absorbed Photosynthetically Active Radiation (fAPAR) is a crucial variable for assessing global carbon balances and currently, there is an urgent need for reference data to validate satellite-derived fAPAR products. However, it is well-known that fAPAR ground measurements are associated with considerable uncertainties. Generally, fAPAR measurements can be carried out with two-, three- and four-flux approaches, depending on the number of flux terms measured. Currently, not much is known about the number of flux terms needed to satisfactorily reduce systematic errors. This study investigates the accuracy of different fAPAR estimates based on permanent, 10-min PAR measurements using Wireless Sensor Networks (WSNs) at three forest sites, located in Central Europe (mixed-coniferous forest), North America (boreal-deciduous forest) and Central America (tropical dry forest). All fAPAR estimates reflect the seasonal course of fAPAR. The highest average biases of different fAPAR estimates account to 0.02 at the temperate, 0.08 at the boreal and -0.05 at the tropical site, respectively, thereby generally fulfilling the uncertainty threshold of a maximum of 10 % or 0.05 fAPAR units set by the Global Climate Observing System (GCOS, 2016). During high wind speed conditions at the boreal site, the bias of the two-flux fAPAR estimate exceeded the 0.05-uncertainty threshold. Three-flux fAPAR estimates were not found to be advantageous, especially at the tropical site. Our findings are beneficial for the development of sampling protocols that are needed to validate global satellite-derived fAPAR products.

1. Introduction

Accurate estimates of biophysical variables such as the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) are crucial input variables for many climate and biophysical models (Fatichi et al., 2016; Ryu et al., 2019). By linking available Photosynthetic Active Radiation (PAR) in the wavelength region between 400 and 700 nm to the absorption of plants (Gobron and Verstraete, 2009), fAPAR quantifies the status and dynamics of vegetation and is involved in many ecosystem processes (Mõttus et al., 2011). Thus, fAPAR has been considered as one of the terrestrial Essential Climate Variables (ECVs) by the Global Climate Observing System (GCOS) (GCOS, 2011, GCOS, 2016). Long-term observations of fAPAR are required for assessing and understanding global carbon balances which are an important constraint in understanding global change (Prince and Goward, 1995; Xiao et al., 2018). On the one hand, continuous and spatially distributed reflectance measurements of vegetation by satellite remote sensing have led to an increasing availability of global fAPAR datasets (MODIS products by Myneni et al. (2002) and Pinty et al. (2011); SPOT VEGETATION product by Baret et al. (2011); SPOT VEGETATION & PROBAV products by Camacho et al. (2013); Sentinel-2 product by Weiss and Baret (2016)) and the development of product enhancements and new retrieval algorithms is ongoing (e.g., Cammalleri et al., 2019; Disney et al., 2016; Gitelson, 2019; Li et al., 2017a; Liu et al., 2019, 2018). On the other hand, studies on the validation of global fAPAR products have reported discrepancies against in situ estimates based on various (measurement) approaches (D'odorico et al., 2014; Martínez et al., 2013; McCallum et al., 2010; Pickett-Heaps et al., 2014; Pinty et al., 2011; Tao et al., 2015) that exceed the current uncertainty requirements set by the Global Climate Observing System (GCOS) for fAPAR products, which is the maximum value between 10 % and 0.05 fAPAR units for spatially distributed fAPAR products (i.e. maps) (GCOS, 2011, GCOS, 2016). Discrepancies between different fAPAR products have been mainly attributed to a priori assumptions on the biome type and assumed scattering properties as well as different underlying fAPAR definitions (Pickett-Heaps et al., 2014). In this regard, it should be noted that satellite-derived fAPAR products based on RTM simulations often relate to absorption by green vegetation elements only, referred to

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as “green fAPAR” (GCOS, 2011). However, in field conditions, PAR radiation is also attenuated by trunks and branches so that measurements obtained by PAR sensors consider the absorption of all vegetation components and thus relate to the concept of “total fAPAR” (GCOS, 2011). Another difference related to the definition of fAPAR that is often found in satellite-derived fAPAR products relates to the direction of the illumination source. Whereas “black-sky” fAPAR considers only direct light, “white-sky fAPAR” results from diffuse radiation only (GCOS, 2011). Typically, satellite-derived fAPAR products only consider “black-sky fAPAR”, whereas direct PAR measurements also contain “white-sky fAPAR” (Liu et al., 2019).

Several studies have emphasized that discrepancies between fAPAR products are highest in forest ecosystems (D’odorico et al., 2014; McCallum et al., 2010; Pickett-Heaps et al., 2014; Tao et al., 2015) and particularly high in tropical forest regions (Xiao et al., 2018; Xu et al., 2018). To improve current retrieval algorithms and radiative transfer models (RTMs), several recent studies have emphasized the need for fAPAR ground observations in forest ecosystems (Gobron, 2015; Xu et al., 2018). However, ground observations of fAPAR that are needed for validation studies are generally scarce and compromised in two respects: First, indirect measurement techniques are used, such as fAPAR retrieved from digital hemispherical photography (DHP) (Li et al., 2015; Liu et al., 2019), LAI (Fensholt et al., 2004; Pinty et al., 2011) or fractional (vegetation) cover (Liu and Treitz, 2018; Pickett-Heaps et al., 2014). Recently, more modeling approaches have been preferred (Majasalmi et al., 2017; Wu et al., 2018). Second, existing experimental set-ups for direct fAPAR measurements with the aim of validating satellite-derived products often lack representative sample sizes as only few PAR sensors are used (e.g., D’odorico et al., 2014; Tao et al., 2015). It is well-known that fAPAR varies considerably across different ecosystems and within single forest stands (Leuchner et al., 2011; Ollinger, 2011; Putzenlechner et al., 2019a) so that multiple samples are required (Reifsnyder et al., 1971; Widlowski, 2010).

In theory, direct measurements of fAPAR would require measuring all five flux components of radiative transfer in canopies: incoming PAR, top-of-canopy reflected PAR, transmitted PAR through the canopy, PAR reflected from the soil and PAR fluxes entering the target canopy horizontally (Widlowski et al., 2006). As capturing all five quantities is unfeasible with currently available measurement techniques, fAPAR is estimated by ignoring certain flux terms or making assumptions upon. Depending on the number of flux terms being measured, direct fAPAR measurements are distinguished into two-, three- and four-flux estimates (Widlowski, 2010): The four-flux fAPAR ($fAPAR_4$) estimate ignores horizontal PAR fluxes; the three-flux fAPAR ($fAPAR_3$) estimate makes assumptions on PAR reflected from the background by either assuming PAR reflected from the background to equal to top-of-canopy reflected PAR ($fAPAR_{3(1)}$) or by ignoring PAR reflected from the background ($fAPAR_{3(2)}$); the two-flux fAPAR estimate ($fAPAR_2$) only considers incoming PAR and transmitted PAR through the canopy.

In general, it is known that depending on the selected fAPAR estimate and environmental conditions, in situ fAPAR will be affected by a considerable bias (Widlowski, 2010). In simulations with RTMs, it has been shown that the accuracy of fAPAR measurements depends on illumination conditions, seasonal changes in leaf color as well as changes in albedo of the forest surface (Widlowski, 2010). As for illumination conditions, it has been confirmed in field experiments (Leuchner et al., 2011; Putzenlechner et al., 2019b) that fAPAR estimates are affected by a considerable bias under high solar zenith angles (SZA) (i.e., above 60°) when the ratio of diffuse radiation to incident radiation is low, especially at conifer-dominated forest stands (Majasalmi et al., 2017; Putzenlechner et al., 2019a; Widlowski, 2010). As horizontal fluxes are ignored in all fAPAR estimates, the bias due to SZA can be limited by preferring fAPAR acquired during diffuse light conditions or, more practicable for validation activities, fAPAR acquired closely around the solar noon when SZA is lowest. Concerning the accuracy of $fAPAR_2$, it has been simulated and observed in field conditions that the accuracy of $fAPAR_2$ is affected by seasonal changes in leaf color (i.e. during senescence period), with a possible influence also of wind speed (Putzenlechner et al., 2019b). Among various fAPAR estimators investigated in RTM simulations, $fAPAR_2$ was found to perform best in open forest canopies under typical summer conditions (Widlowski, 2010). These findings, however, seem to be in contrast with the current scientific practice based on available tower-base top-of-canopy reflected PAR. In this regard, the majority of studies using direct fAPAR measurements has preferred to perform three-flux measurements (D’odorico et al., 2014; Nestola et al., 2017; Rankine et al., 2014; Senna et al., 2005; Tao et al., 2015). Given the diversity of experimental set-ups used for direct fAPAR measurements in existing studies (Liu and Treitz, 2018; Nestola et al., 2017; Putzenlechner et al., 2019a; Senna et al., 2005; Steinberg et al., 2006; Tao et al., 2015; Ter-Mikaelian et al., 1999), there seems to be no overall consensus on which measurement approach, i.e. considering two-, three or four flux terms for the estimation of fAPAR, to choose. Thus, it becomes clear that the current situation is characterized by a lack of both well-defined field protocols and understanding of uncertainties involved in fAPAR measurements (Gobron, 2015).

During the last decade, WSNs have opened up new possibilities in environmental monitoring by ensuring cost and labor efficient options for multi-sensor and multi-temporal sampling also in forest ecosystems (Pastorello et al., 2011). Although WSNs have already demonstrated their potential for fAPAR observations and the validation of satellite-derived fAPAR products (Nestola et al., 2017; Putzenlechner et al., 2019a), WSN with multiple PAR sensors have not been used to evaluate the accuracy of two-, three and four-flux estimating schemes. Thus, former studies could not refer to any practical guidelines for sampling protocols on how to select a certain estimating scheme. To bridge this gap, the aim of this study is to assess the bias involved in different fAPAR estimates with direct PAR measurements using WSNs at three different forest sites: a temperate mixed-coniferous forest in Central Europe, Germany, a boreal-deciduous forest in Alberta, Canada and a tropical dry forest (TDF) in Costa Rica. Given existing findings from RTMs (Widlowski, 2010) and first experiences with uncertainties of two-flux fAPAR observations available at the temperate site (Putzenlechner et al., 2019b), one could assume that the two-flux FAPAR estimate does not exceed the uncertainty requirements set by the GCOS (2016). Thus, we will assess the hypothesis that the absolute differences between two- and three-flux estimates compared to the four-flux estimate remain within 0.05 in fAPAR units during the vegetation period irrespective of the type of ecosystem. Our approach follows the underlying assumption that the four-flux approach is very close to “true” fAPAR. Our main objectives were then to a) perform permanent, multi-sensor two-, three- and four-flux fAPAR measurements, b) assess the estimation bias associated with different fAPAR estimates and c) assess and evaluate uncertainties associated with certain seasonal or environmental conditions that have been found to lead to bias, such as the presence of colored autumn leaves, snow covered forest floor, or higher wind speeds. Our evaluation on the bias involved in different fAPAR estimating schemes in three different forest ecosystems will improve the knowledge on uncertainties involved in fAPAR ground estimates. We will also derive practical recommendations on how to improve experimental set-ups and sampling protocols needed to validate satellite-derived fAPAR products.

2. Materials and methods

2.1. Study sites

Permanent fAPAR observations were carried out in three different forest ecosystems: a mixed-coniferous forest in Central Europe, a boreal-deciduous forest in North America and a tropical dry forest (TDF) in Central America (Fig. 1). The European site “Graswang” is

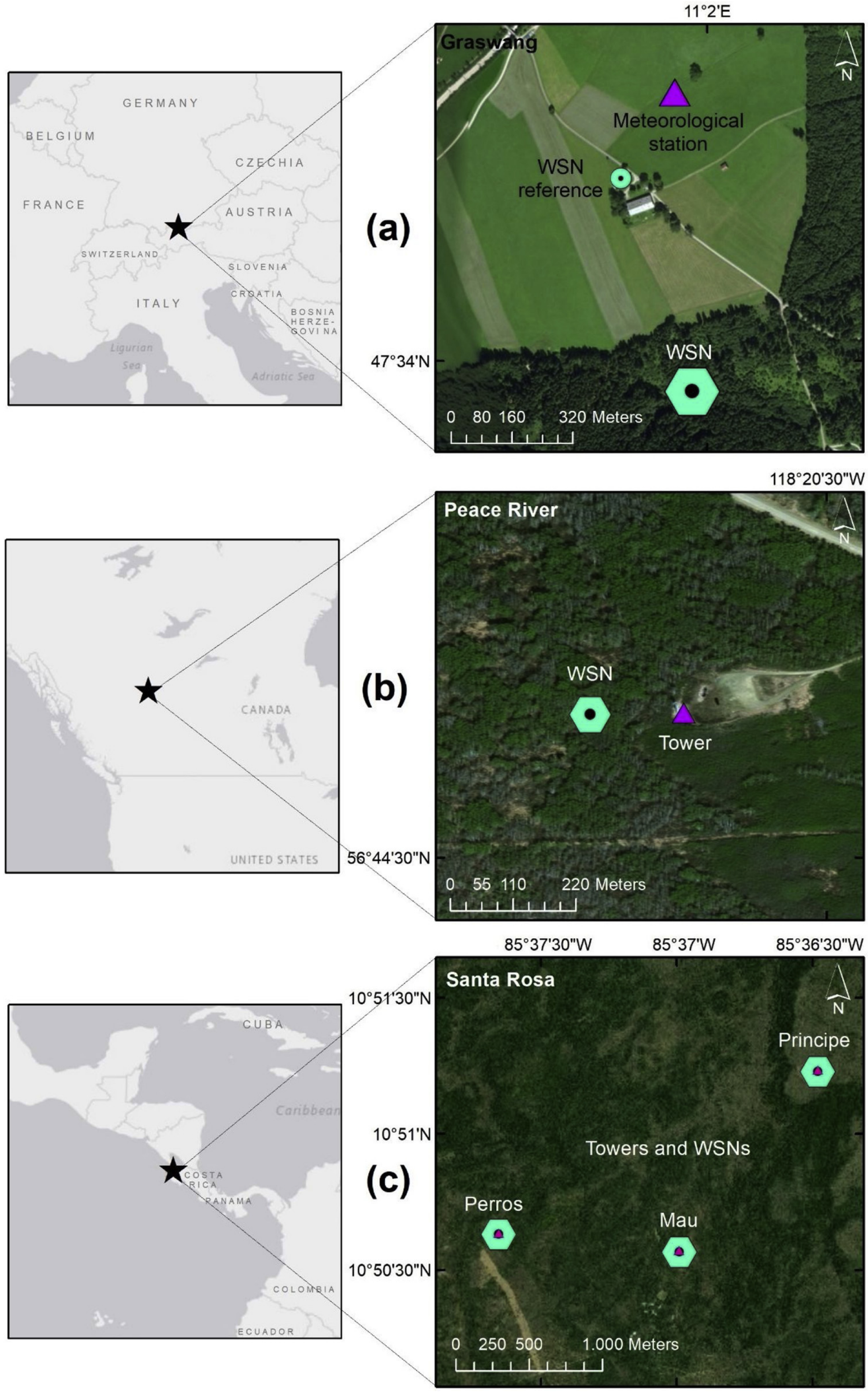


Fig. 1. Locations and set-up of the three WSN study sites for permanent fAPAR observations: (a) Graswang, (b) Peace River and (c) Santa Rosa. Hexagonal symbols refer to WSNs, triangles refer to towers with meteorological and carbon/water flux eddy covariance stations.

located in Southern Germany in a sub-alpine valley and comprises a mid-aged forest stand composited of both conifers (82 % Norway spruce/*Picea abies (L.) H.Karst*) and broadleaf tree species (14 % European beech/*Fagus sylvatica* L., 4 % sycamore maple/*Acer pseudoplatanus* L.). The understory vegetation comprises low growing herbs not taller than 30 cm (i.e., wood sorrel/*Oxalis acetosella* L., dog's mercury/*Mercurialis perennis* L.). Climate is warm-temperate and fully humid, with a vegetation period typically starting in late April and ending in late September. Snowfall occurs frequently throughout the dormant period. The site is part of the pre-Alpine TERENO research observatories (Zacharias et al., 2011). In addition to existing environmental monitoring equipment (e.g. meteorological station outside the forest) (Zeeman et al., 2017), the site was equipped with a WSN of PAR sensors to carry out permanent fAPAR observations (Putzenlechner et al., 2019b). A forest inventory revealed that average tree height accounted 15 m, stem density and basal area accounted 231 stems $(0.1\ ha)^{-1}$ and 4.8 m^2 $(0.1\ ha)^{-1}$, respectively.

The North American "Peace River Environmental Monitoring Super Site" ("Peace River") is located in Northern Alberta, Canada (Fig. 1) and comprises an old-growth boreal-deciduous forest stand with tree heights reaching up between 15 and 20 m (Rankine et al., 2014; Taheriazad et al., 2016). The forest stand is dominated by trembling aspen (*Populus tremuloides Michx.*) which is typical for the Northern Albertan biome of aspen parkland (Parks, 2006). The understory vegetation comprises a second vertical layer of canopy (predominantly mountain alder/*Alnus crispa*, prickly rose/*Rosa acicularis Lindl.*), reaching up to 4 m (Rankine et al., 2014). Average tree height accounts to 27 m, basal area and stem density is 4.1 stems $(0.1\ ha)^{-1}$ and 2.4 m^2 $(0.1\ ha)^{-1}$, respectively. The climate can be classified as humid-continental, with cool summers and snowy winters and thus a relatively short vegetation period, typically spanning from mid of May to mid of September. The site is part of the joint industry-research forestry region for Ecosystem Management Emulating Natural Disturbance (EMEND) for large-scale boreal forest preservation and harvest experimentation (Spence and Volney, 1999). Besides the WSN, the site comprises a 30 m tall flux tower for detailed meteorological and carbon/water flux observations.

The Central American "Santa Rosa National Park Environmental Monitoring Super Site" ("Santa Rosa") is located in the Province of Guanacaste, Costa Rica (Fig. 1 and comprises a TDF under different levels of successional stages. In the tropical-monsoonal climate, vegetation period spans typically from May to December, followed by a 5-months dry season. Annual precipitation is approx. 1750 mm but can be highly variable Kalacska et al., 2004). Before the area became a conservation area in 1971, Santa Rosa was a cattle ranch. Today, the park is a mosaic of forests under different successional stages of secondary dry forests (Li et al., 2017b). For this study, we used data from three sub-sites, named "Kakubari", "Perros" and "Principe" which are all located in TDF of an intermediate successional stage. This stage is characterized by two layers of canopy with a large variety of deciduous and few evergreen species (e.g., bastard cedar/*Guazama ulmifolia Lam.*, *Luehea speciose Willd.*, *Lonchocarpus minimiflorus Donn. Smith*, *Byrsonima crassifolia* (L.) *Kunth*) and an understory composed of lianas and shade tolerant species (e.g., *Amphilophium paniculatum* (L.) *Kunth*, *Davila kunthii A. St.-Hil.*, *Annona reticulata* L., *Ocotea veraguensis (Meisn.) Mez*, *Hirtella racemose Lam.*) (Arroyo-Mora et al., 2005; Kalacska et al., 2004). In a forest inventory, average tree height and basal area for all three sub-sites accounted 10 − 15 m, 120 stems $(0.1\ ha)^{-1}$ and 1.9 m^2 $(0.1\ ha)^{-1}$, respectively. All sub-sites are equipped with 35 − 40 m high carbon flux towers, each of them surrounded by a WSN ("Kakubari", "Perros" and "Principe", Fig. 1).

2.2. Wireless sensor networks for permanent fAPAR observations

At all three sites, WSNs were deployed for permanent fAPAR observations. The set-up for fAPAR observations included commercially available quantum PAR sensors (model SQ-110, Apogee, Logan, UT, USA; field of view 180°; uncertainty estimates: cosine response ± 5 % at 75 °SZA, temperature response 0.06 ± 0.06 % per °C, calibration uncertainty ± 5 % and non-stability $< 2\ \%\ y^{-1}$) that were connected to self-powered nodes (model ENV-Link-Mini-LXRS, LORD MicroStrain, Cary, NC, USA). The configuration of the WSNs and scheduled data downloads during maintenance activities were carried out with a portable receiver (frequencies ranging from 2.405 GHz to 2.480 GHz). This "base station" was equipped with USB interface (model WSDA-Base-104 USB Base Station, MicroStrain, Cary, NC, USA) so that it can be connected to a portable computer equipped with the software "Node Commander" for network configuration and downloads (version 2.17.0, LORD MicroStrain, Cary, NC, USA). Due to the reduced accessibility of the sites Peace River and Santa Rosa, data aggregation was also carried out operationally with a base station equipped with an outdoor receiver (model WSDA-1000 Wireless Sensor Data Aggregator, MicroStrain, Cary, NC, USA) positioned on the towers. A cellular GSM modem pointed at the nearest cellular tower enabled internet access most of the times and a battery bank (200 Ah) combined with solar panels (75 W) ensured power supply (Pastorello et al., 2011; Rankine et al., 2014). At all sites, WSN nodes were configured to measure instantaneous PAR every 10 min synchronously (~1 ns). Data was uploaded to "Enviro-Net" (http://www.enviro-net.org/), a web platform for sensor data management, near real-time visualization and analysis (Pastorello et al., 2011). For this study, PAR data acquired at the three study sites during the respective vegetation periods of the year 2016 was used.

2.2.1. Measurements of incoming and transmitted PAR

Sensors for monitoring incoming (PAR_{in}) and transmitted PAR (PAR_{trans}) were installed directed upward and mounted on wooden poles at 1.3 m height to avoid influences from ground-level vegetation. Angle connectors were used to ensure correct leveling of sensors. At Graswang, the reference sensor for PAR_{in} was located on open grassland (Fig. 1c), while it was measured right above the WSNs on towers at Peace River and Santa Rosa Environmental Monitoring Super Sites (Fig. 1**a-b**). All sensors for PAR_{trans} were deployed in hexagonal geometry (Fig. 2) since this sampling scheme has been found to ensure signal quality and connectivity (Mortazavi et al., 2014; Younis and Akkaya, 2008) while at the same time maximizing the sensing area covered by a given number of nodes which, in turn, is important to reduce sampling bias (Widlowski, 2010). From previous investigations on the spatial variability of the radiation field in forests, it is known that fAPAR will depends mainly on the chance of sensor location when less than ten nodes are used for calculating the domain fAPAR (Putzenlechner et al., 2019b; Widlowski, 2010). To ensure the representativity of domain fAPAR, we deployed a minimum of 16 sensors per site. PAR_{trans} was acquired with 16 sensors at Graswang, 22 sensors at Peace River and 35 sensors at Santa Rosa (19 at "Kakubari", 10 at

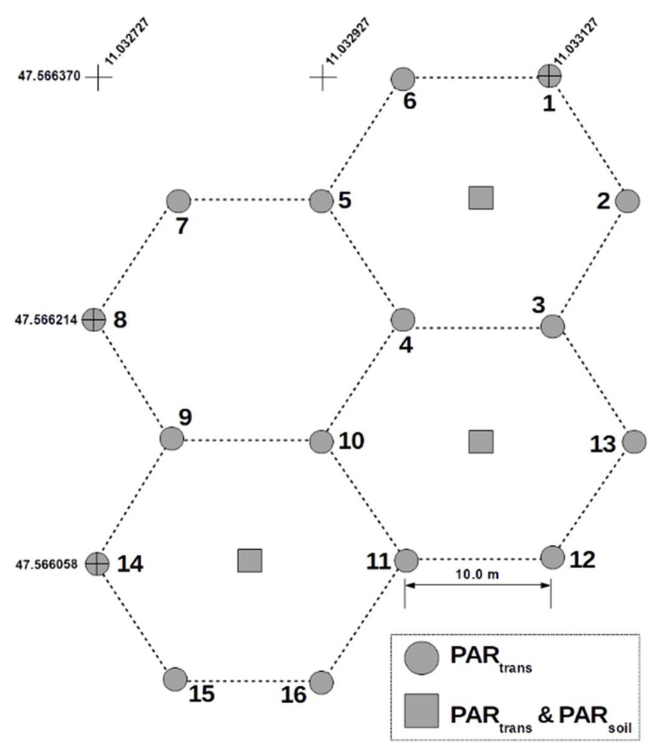


Fig. 2. Example of the experimental setups of the WSNs nodes, consisting of a hexagonal sampling scheme; at the temperate site Graswang, the WSN consisted of 16 nodes with sensors for transmitted PAR and three nodes for transmitted and soil-reflected PAR to calculate the forest background albedo (R_{soil}).

"Principe" and 6 at "Perros"), respectively. As average canopy heights are different among the study sites, we considered different spatial footprints of PAR_{trans} measurements by deploying WSN nodes with 20 m spacing at Peace River and Santa Rosa and 10 m spacing at Graswang.

2.2.2. Observations of top-of-canopy PAR albedo

Observations of top-of-canopy PAR albedo (R_{TOC}) are required to calculate three- and four-flux fAPAR estimates. Ideally, R_{TOC} is determined continuously for each timestep from the following equation:

$$R_{TOC_n} = \frac{1}{n}\sum_{i=1}^{n}\frac{PAR_{TOC_i}}{PAR_{in_i}} \tag{1}$$

With sensor location i, number of sensors n, PAR_{TOC} as PAR reflected upward from top-of-canopy and PAR_{in} as incoming PAR. At the sites Peace River and Santa Rosa (including sub-sites "Kakubari", "Perros" and "Principe"), R_{TOC} was determined continuously every 10 min at the 30 m high flux towers with two opposite quantum PAR sensors connected to an environmental monitoring node which was synchronized with all WSN observations. At Graswang, the installation of a tower was not possible due to site-specific legal restrictions. Instead, R_{TOC} was approximated by PAR observations carried out with an Unmanned Aircraft Vehicle (UAV) (Brosy et al., 2017) twice per year to cover the partly and fully foliated vegetation periods (**Appendix A**, **Table A1**). Therefore, an environmental monitoring node with a downward looking PAR sensor was mounted onto a commercially available hexacopter (model DJI F550 Flame Wheel, DJI Innovations, Shenzhen, China) to measure the reflected PAR above the canopy at 1 Hz temporal resolution. The hexacopter was equipped with an autopilot (Pixhawk, 3DR, Berkeley, USA) and an external GPS (LEA-6 u-blox 6, u-blox, Thalwil, Switzerland). Flight specific data was logged on board (attitude angles as well as engine output at 10 Hz, the accelerometer and gyroscope data at 50 Hz and GPS at 5 Hz), temporally aggregated to 1 Hz and joined with the PAR measurements. The takeoff weight including devices for PAR measurements accounted to approx. 2 kg which limited battery life and thus flight durations to 10 min. The UAV was programmed to aim for a relative altitude around 35 m after departure to ensure a vertical distance of 20 m to the tree crowns. As the UAV was started from the grassland approx. 100 m away from the area occupied by the WSN, the geo-coordinates tracked by the onboard GPS systems were used to select the timesteps for which the device was flying right above the WSN. For R_{TOC}, the ratio between PAR_{TOC} (as acquired during flights) and PAR_{in} (on the grassland) was calculated. To avoid influences of different illumination conditions resulting from moving clouds, flights were only carried out during clear sky conditions. Further, flights could not be carried out during high wind speeds or diffuse illumination conditions due to poor visibility of the UAV. Finally, the mean of the resulting four values for R_{TOC} (**Appendix A**, **Table A1**), which accounted to 0.03, was used as constant to calculate the four-flux fAPAR estimate at Graswang.

2.2.3. Observations of forest background PAR albedo

Permanent observations of forest background albedo (R_{soil}) are needed to calculate the four-flux fAPAR estimate. Therefore, measurements of PAR reflected from the forest soil (PAR_{soil}) were carried out with downward directed PAR sensors with 10 min sampling interval (synchronized with all other WSN observations). The forest background PAR albedo R_{soil} for the whole site for each timestep was calculated as follows:

$$R_{soil} = \frac{1}{n}\sum_{i=1}^{n}\frac{PAR_{soil_i}}{PAR_{trans_i}} \tag{2}$$

With sensor location i, number of sensors n, PAR_{soil} as PAR reflected upward from the forest floor and PAR_{trans} as transmitted PAR from the canopy.

At Graswang, three WSN nodes were installed at 3 m height across the area covered by the WSN (Fig. 1d, Fig. 2). Measurements of PAR_{soil} were amended by another sensor for PAR_{trans} pointed upward into the leafy canopy. The nodes with the two opposite quantum PAR sensors were covered and protected from weathering in plastic boxes that were attached to four neighboring trees with solid plastic ropes, respectively. Correct leveling of the constructions was checked every 10–20 days. At the Peace River and Santa Rosa Environmental Monitoring Super Sites, installations in trees were not possible due to various site/ecosystem constraints. Specifically, constructions hanging in trees were devastated by wildlife (i.e., bears) shortly after their installation at Peace River and too difficult to install and maintain at Santa Rosa due to the poor accessibility of the forest due the natural occurrence of lianas. In addition to these practical reasons, the presence of two distinct vertical layers of canopy and especially its high volumetric variability in the TDF would have complicated the selection of representative areas for measuring forest background albedo from several meters above the forest floor. Instead, downward directed PAR_{soil} sensors were mounted at three nodes for PAR_{trans} of the WSNs at Peace River and 6 at Santa Rosa (i.e. at sub-site "Kakubari"), respectively.

2.2.4. Processing of PAR data and calculation of fAPAR estimates

Before calculating fAPAR estimates, site-specific pre-processing of PAR data was carried out for data acquired at the site Graswang. Due to the surrounding slopes, we had to consider that the WSN was periodically affected by topographic shadowing. Therefore, potentially affected time steps were determined and deleted for each sensor location based on the solar position and a Digital Elevation Model (DEM 5 m, Free State of Bavaria, https://www.ldbv.bayern.de) using the R-package "insol" (Corripio, 2003). As the WSNs at Santa Rosa and Peace River are located on relatively flat terrain, topographic shadowing did not occur. At Graswang site, we also had to consider that moving clouds may cause bias in fAPAR estimates, as sensors for PAR_{in} and PAR_{trans} are separated by 300 m. For the case that the reference sensor outside the forest was shadowed by clouds, we checked whether PAR_{trans} exceeded PAR_{in} and eliminated respective timesteps from the dataset. Regarding Peace River and Santa Rosa Environmental Monitoring Super Sites, we assumed errors caused by cloud shadowing to be negligible as PAR_{in} and PAR_{TOC} were acquired on flux towers adjacent to sensors for PAR_{trans} and PAR_{soil}.

Subsequently, PAR measurements carried out at 10 min temporal resolution were processed to two-, three- and four-flux fAPAR estimates. The domain-level (i.e. representative for one study site) two-flux fAPAR estimate $fAPAR_{2n}$ was calculated as follows:

$$fAPAR_{2_n} = \frac{1}{n}\sum_{i}^{n} 1 - \frac{PAR_{trans_i}}{PAR_{in_i}} \tag{3}$$

with sensor location i, number of sensors n, PAR_{trans} as PAR transmitted through the canopy and PAR_{in} as incoming PAR. For the domain-level three-flux fAPAR estimates ($fAPAR_{3n}$), we distinguished into $fAPAR_{3(1)n}$ (hypothesis: $R_{soil} = R_{TOC}$) and $fAPAR_{3(2)n}$ (hypothesis: $R_{soil} = 0$) which were calculated as follows:

$$fAPAR_{3(1)_n} = \frac{1}{n}\sum_{i}^{n} (1 - R_{TOC_n})(1 - \frac{PAR_{trans_i}}{PAR_{in_i}}) \tag{4}$$

$$fAPAR_{3(2)_n} = \frac{1}{n}\sum_{i}^{n} 1 - R_{TOC_n} - \frac{PAR_{trans_i}}{PAR_{in_i}} \tag{5}$$

with top-of-canopy PAR albedo R_{TOC}. The domain-level four-flux fAPAR estimate $fAPAR_{4n}$ was calculated as follows:

$$fAPAR_{4_n} = \frac{1}{n}\sum_{i}^{n} 1 - R_{TOC_n} - \frac{PAR_{trans_i}}{PAR_{in_i}}(1 - R_{soil_n}) \tag{6}$$

with PAR albedo of the forest floor R_{soil}.

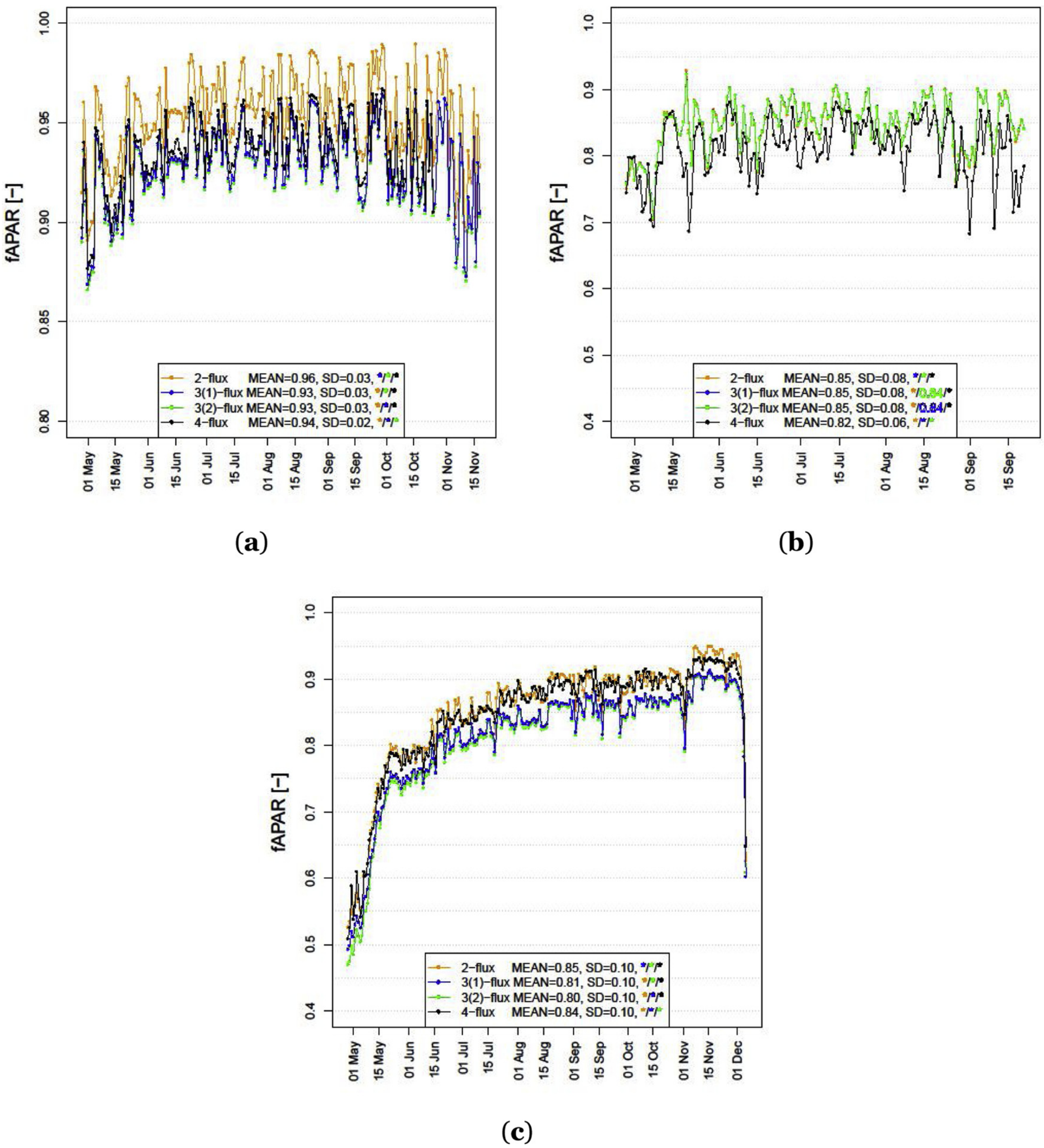


Fig. 3. Seasonal course of daily aggregated two-, three- and four-flux 10-min fAPAR estimates at the three study sites for the year 2016 at (**a**) Graswang, (**b**) Peace River and (**c**) Santa Rosa. Note that value ranges on y-axis are different for (**a**) compared to (**b**, **c**). The legend shows MEAN, SD of the whole time series and gives *p*-values obtained from a KS test for pairs of fAPAR distributions, with * indicating $p < 0.05$; the colors indicate pairs of comparison.

2.3. Meteorological and phenological observations

At Graswang, records of wind speed were used from the TERENO meteorological station (model WXT520, Vaisala, Vantaa, Finland) on open grassland (Appendix B**, Figure B1a**). Information on forest phenology and the occurrence of snow were retrieved from an automated camera (model SnapShot Mini 5.0, Dörr, Neu-Ulm, GER) installed at 1.3 m height and directed horizontally towards the center of the WSN in the forest. Based on visual inspection of daily photos, we classified the phenological status of the canopy as "no leaves", "green leaves", "yellow leaves" and "red leaves". Regarding the factor snow, we distinguished into no occurrences of snow ("no") and partly or closed snow cover ("yes"). Dates and representative photos for these conditions are shown in **Appendix C** (**Table C1**, **Table C2**, **Figure C3**). At Peace River, wind speed was acquired with the meteorological station (HOBO Energy Pro, OneTemp Pty Ltd, Adelaide, AU) at the flux tower above the forest. At Santa Rosa, records were taken at the towers of each of the sub-sites (same product specification as at Peace River). As the environmental conditions and circumstances at Peace River and Santa Rosa did not allow for permanent observations with automated cameras, the phenological status was approximated by subletting the fAPAR observations by season, i.e. acquired during fully foliated season (i.e., Peace River: 01 Jun-31 Aug; Santa Rosa: 01 Jun-30 Sep) and partly or defoliated season (i.e., rest of available fAPAR time series).

2.4. Statistical analysis

This study assessed and explored absolute and relative differences between fAPAR estimates ($fAPAR_2$, $fAPAR_3$, $fAPAR_4$) and the influence of phenological and meteorological conditions upon these differences. This was done by the means of statistical testing, calculation of performance metrics and a multifactorial ANOVA. To test fAPAR distributions up on equality of distributions as null hypothesis (0.05-significance level), the nonparametric Kolmogorov-Smirnov test (KS test) was applied. Further, a correlation analysis between different fAPAR estimates was performed using BIAS and R2 as performance metrics. For assessing systematic relative offsets, we calculated the mean difference between value pairs (BIAS), i.e. the average tendency of $fAPAR_2$ and $fAPAR_3$ estimates to be larger or smaller than the $fAPAR_4$ estimate. Note that we considered $fAPAR_4$ as reference ("closest to truth") as it incorporates the highest number of measured flux terms of the radiative equation for fAPAR. We compared BIAS following the uncertainty requirements set by the GCOS (2016), demanding an uncertainty of the maximum between 10 % and 0.05 ("MAX(10 %; 0.05)") for spatially distributed fAPAR products (i.e., maps). In our study, the 0.05-threshold was chosen as a fixed baseline as our dataset is based on point measurements (not maps, as defined by the GCOS) and thus contained single timesteps for fAPAR values acquired at individual sensor locations below 0.05, especially during early and late vegetation period. Further, we calculated the squared Pearson correlation coefficient (R^2) to indicate the goodness of fit regarding a linear regression model between $fAPAR_2$ or $fAPAR_3$ estimates and $fAPAR_4$.

A multifactorial analysis of variation (ANOVA) was applied to evaluate the effect of environmental conditions on the difference of fAPAR estimates. As high wind speeds occurred less frequently at all three sites and high wind speeds have been suspected to decrease observed fAPAR values in previous investigations (Putzenlechner et al., 2019b), we classified wind speed data into two levels: wind speed < 2 ms^{-1} and wind speed ≥ 5 ms^{-1}. As detailed phenological and meteorological observations were available at Graswang, we investigated the influence of leaf status, occurrence of snow and (classified) wind speed as factors on the difference between $fAPAR_2$ or $fAPAR_3$ and $fAPAR_4$ at each 10-min timestep ($bias_{2to4}$, $bias_{3(1)to4}$, $bias_{3(2)to4}$), respectively. At the sites Peace River and Santa Rosa, we investigated the influence of season (only distinguished into levels "fully foliated" and "partly foliated/defoliated") and (classified) wind speed on $bias_{2to4}$, $bias_{3(1)to4}$, $bias_{3(2)to4}$, respectively. Significant differences in respective values of $bias_{2to4}$, $bias_{3(1)to4}$, or $bias_{3(2)to4}$ according to environmental conditions were identified from *F*- and respective *p*-values.

3. Results

3.1. Seasonal dynamics of different fAPAR estimates and bias

The permanent monitoring resulted in almost continuous time series of different fAPAR estimates at all three sites (Fig. 3). At Graswang, $fAPAR_4$ was not available from end October onwards due to failures of sensors for PAR_{soil} (Fig. 3a). The seasonal courses of all fAPAR estimates reflect the phenological development, showing an increase of fAPAR in spring, a decrease of fAPAR values at the end of the growing season and in-between a plateau phase that is most pronounced at the temperate site. Compared to the other sites, the temperate site Graswang exhibits a relatively low range of fAPAR values (approx. 0.15 fAPAR units), with all estimates showing values rarely below 0.90. In contrast, a relatively high seasonal range (approx. 0.20 fAPAR units at Peace River and approx. 0.40 fAPAR units at Santa Rosa) is observed at the deciduous forests of Peace River and Santa Rosa (Fig. 3**b-c**). Apart from the differences in seasonal dynamics, mean values of all fAPAR estimates (0.93-0.96) at Graswang are considerably higher than at Peace River (0.82-0.85) and Santa Rosa (0.80-0.85).

Seasonal dynamics of different fAPAR estimates appear similar in Fig. 3 which is confirmed by the strong linear relationships depicted in Fig. 4, showing R^2 between 0.93 and 0.98. Across all sites, minimum BIAS between different fAPAR estimates account to -0.50 at Graswang, 3.30 at Peace River and 0.40 at Santa Rosa (Fig. 4b, **f**, **g**). Still, there are significant differences between most fAPAR estimates (KS test: $p < 0.05$, see legends in Fig. 3). It can be seen that at the temperate and boreal sites, BIAS between $fAPAR_2$, $fAPAR_{3(1)}$ or $fAPAR_{3(2)}$ and $fAPAR_4$ decrease with increasing number of flux terms considered (Fig. 4**a-f**): At Graswang, the lowest and highest BIAS (-0.01; 0.02) with $fAPAR_4$ was obtained for $fAPAR_2$ and $fAPAR_{3(1)}$, respectively; at Peace River, $fAPAR_2$ shows considerably higher BIAS (0.08) when related to $fAPAR_4$ than $fAPAR_{3(1)}$ (BIAS: 0.03). However, at the tropical site, $fAPAR_2$ shows marginal deviations with $fAPAR_4$ compared to $fAPAR_{3(1)}$ and $fAPAR_{3(2)}$ (Fig. 4**g-i**).

Apart from absolute values of BIAS, another feature to be considered in the evaluation of different fAPAR estimates is the sign of BIAS. In this regard, value distributions of the bias depicted in Fig. 5 show that most values obtained for $bias_{2to4}$ are positive. Thus, $fAPAR_2$ overestimated $fAPAR_4$ at all three sites. Further, even though value distributions of $bias_{3(1)to4}$ and $bias_{3(2)to4}$ show similar shape and the same median values at each of the sites, values are both positively and negatively signed. As a striking feature, the median of 0.05 obtained at the boreal site (Fig. 5b) indicates that for half of the timesteps, $bias_{2to4}$ has crossed the uncertainty target following the GCOS (2016).

3.2. Environmental conditions and their effect on bias between fAPAR estimates

We investigated, whether environmental conditions, i.e. the factors wind speed and season at Peace River and Santa Rosa or rather the factors wind speed, leaf status and snow at Graswang, influenced the bias between two- or three-flux estimates and $fAPAR_4$ (i.e., $bias_{2to4}$, $bias_{3(1)to4}$, $bias_{3(2)to4}$). Table 1 presents the results of the respective two- or three-factorial ANOVAs with $bias_{2to4}$, $bias_{3(1)to4}$, $bias_{3(2)to4}$ as target variables (for MEAN and SD, see **Appendix D**).

3.2.1. Seasonal and phenological effects

For all sites, the ANOVA results show significant (i.e., $p < 0.05$) seasonal (i.e. factor season) or phenological (i.e. factor leaf status) effects on the bias of fAPAR estimates (Table 1, Fig. 6). At Graswang, $bias_{2to4}$ was increased for the leaf status "yellow" and "no leaves", while for the three-flux estimates, a slightly higher bias was obtained for red leaves, even though the effect was less pronounced for $bias_{3(1)to4}$ (Fig. 6b). In contrast to leaf status, no significant effect of snow was found (Table 1, Fig. 6a). At the boreal and tropical site, the more generalized factor "season" showed significant effects on the bias of several fAPAR estimates ($bias_{2to4}$ at Peace River and $bias_{3(1)to4}$ at Santa Rosa and Peace River, see Table 1). The higher *F*-values obtained from the ANOVA indicates that the effect of season on the bias of fAPAR was more pronounced at the boreal site. In addition to that, the median of $bias_{2to4}$ crosses the 0.05-uncertainty threshold following the GCOS (2016) requirements for both foliated and defoliated season (Fig. 6c), while at the tropical site, values of $bias_{2to4,}$ $bias_{3(1)to4}$ and $bias_{3(2)to4}$ stay within the -0.05 and 0.05-range irrespective of the fAPAR estimate (Fig. 6d).

3.2.2. Influence of wind speed

Wind speed influenced the bias of fAPAR estimates to various extents, depending on the site and fAPAR estimate. At Graswang, all estimates show deviations to $fAPAR_4$ below 0.05 (Fig. 7a), which is also reflected in the similar *F*-values in the ANOVA (Table 1). Here, only for $bias_{3(1)to4}$ a significant effect ($p < 0.05$) was found. At the boreal and tropical sites, the effect of wind speed on the bias was found to be highly significant ($p < 0.001$) for almost all estimates (Table 1). At Peace River, it is clearly visible that the 0.05-uncertainty threshold is crossed permanently for $bias_{2to4}$ during wind speeds between 2 and 3 ms^{-1} as well as above 4 ms^{-1} (Fig. 7b). At Santa Rosa, the effect of wind speed is significant, but fulfill the uncertainty requirements (Fig. 7c). Wind speed was found to affect top-of-canopy PAR albedo (R_{TOC}). In this regard, Fig. 8 shows that with increasing wind speed, R_{TOC} increases by 36–38 % at Santa Rosa and Peace River, respectively.

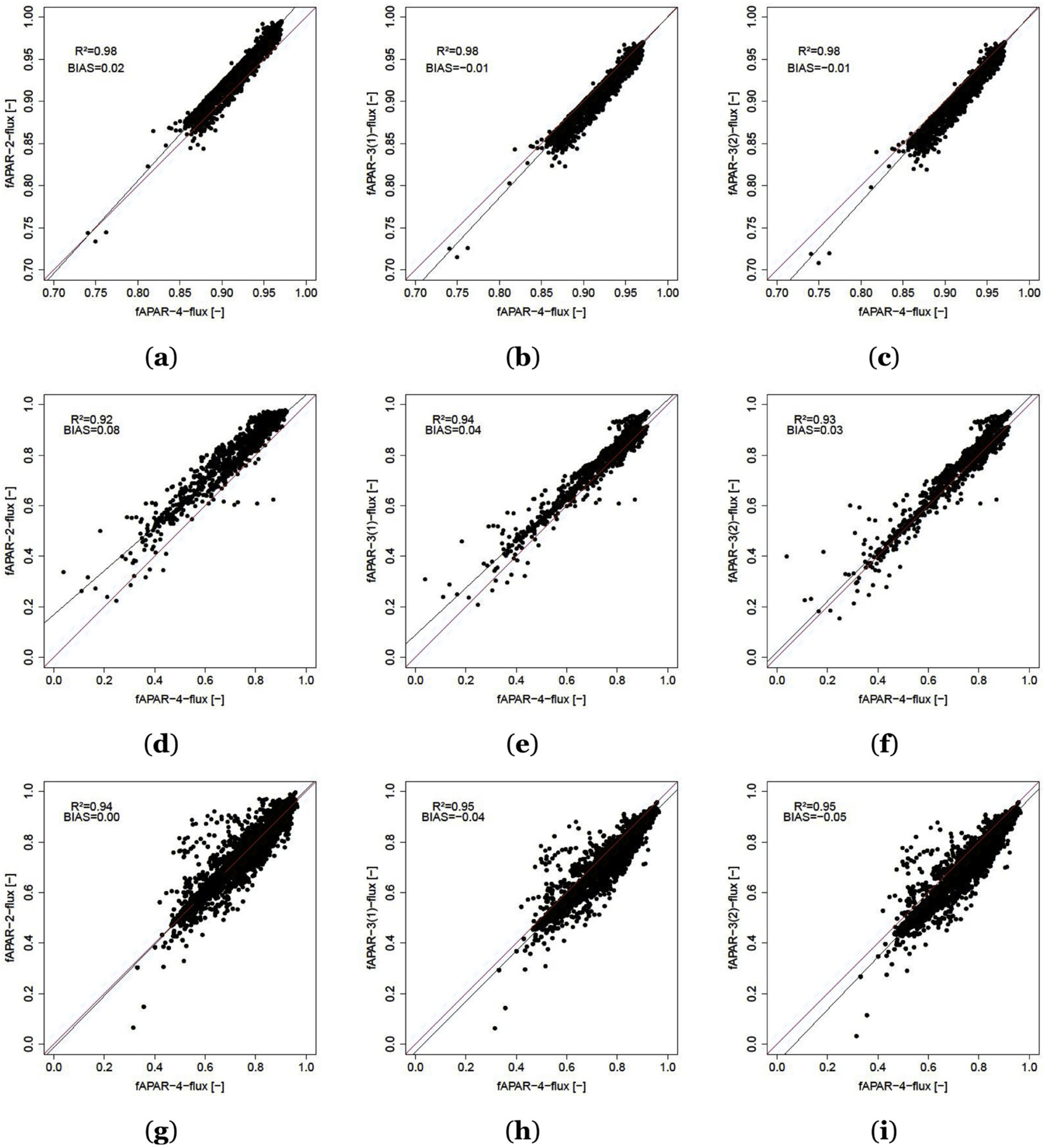


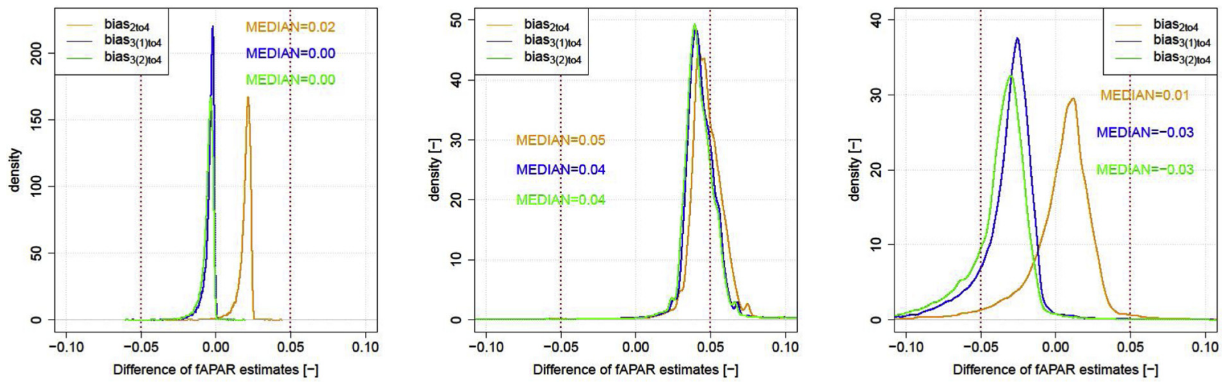
Fig. 4. Scatterplots of $fAPAR_2$, $fAPAR_{3(1)}$ and $fAPAR_{3(2)}$ vs. $fAPAR_4$ at (**a**-**c**) Graswang, (**d**-**f**) Peace River and (**g**-**i**) Santa Rosa. Mean average deviation between pairs of values (BIAS) and coefficient of determination (R^2) are shown. The continuous black line corresponds to slopes and intercepts of the linear regression, while the red line marks the 1:1 line. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

4. Discussion

4.1. Consistency of fAPAR estimates and overall accuracy

We presented time series of two-, three- and four-flux fAPAR measurements (referred to as "fAPAR estimates") for the vegetation period of 2016 using WSNs in three different forest ecosystems: the temperate mixed-coniferous forest site Graswang, Germany, the boreal-deciduous forest site Peace River in Northern Alberta, Canada and the tropical dry forest (TDF) site Santa Rosa, Costa Rica. All fAPAR estimates reflect the seasonal increase and decrease of fAPAR values and show relatively high fAPAR with absolute values above 0.7 during the growing season (Fig. 3), which is typical for forests (e.g., Leuchner et al., 2011; Majasalmi et al., 2017; Nestola et al., 2017). The relatively low seasonal dynamic with a seasonal range of only 0.15 fAPAR units at Graswang reflects the dominance of evergreen conifers at this site (Fig. 3a). Additionally, the relatively high values could be attributed to the higher basal area and stem density when compared to Peace River and Santa Rosa.

Based on the fAPAR time series, we assessed overall differences between fAPAR estimates with several performance metrics (Fig. 4). The high overall correlations with R^2 above 0.9 between fAPAR estimates indicate that adding information on top-of-canopy PAR albedo (R_{TOC}) and forest background albedo (R_{soil}) did not alter the time series in terms of seasonal dynamics considerably. This can be explained by the fact that PAR_{trans} represents the flux component with by far the



(a) (b) (c)

Fig. 5. Density of the difference between two- or three-flux estimates and the four-flux fAPAR estimate ($bias_{2to4}$, $bias_{3(1)to4}$, $bias_{3(2)to4}$) calculated for each 10-min timestep for the year 2016 at (**a**) Graswang, (**b**) Peace River and (**c**) Santa Rosa.

highest proportion in the absorption in the PAR range (Widlowski, 2010). As average bias between $fAPAR_2$, $fAPAR_{3(1)}$ and $fAPAR_{3(2)}$ with $fAPAR_4$ was found to be lower than the uncertainty requirements following the GCOS (2016), our initial hypothesis that the bias of two- and three-flux fAPAR estimates are within acceptable ranges, could be confirmed. Under the assumption that $fAPAR_4$ was closest to "true" fAPAR, we found an overestimation bias of $fAPAR_2$ at all three sites (i.e., majority of values of $bias_{2to4}$ with positive sign in Fig. 5), which is in accordance with previous findings from RTM simulations (Widlowski, 2010). For $fAPAR_3$, results were not as distinct (Fig. 5) and when taking a closer look at overall bias between the time series, it is striking that differences between fAPAR estimates did not necessarily decrease with increasing number of flux terms considered (Fig. 4).

In theory, one would expect that considering additional flux terms for fAPAR decreased the estimation bias. However, we could only see a reduction of the bias at the temperate site Graswang (Fig. 4**a-c**). At the boreal site, bias was barely reduced for the three-flux estimates and it is particularly striking that $fAPAR_2$ presented lower deviations to $fAPAR_4$ than the three-flux fAPAR estimates at the tropical site Santa Rosa. As for Peace River, the fact that there was almost no difference between the value distributions of three-flux fAPAR estimates (Fig. 5b) suggests that R_{soil} was very different to R_{TOC} and could thus not be approximated with R_{TOC} ($fAPAR_{3(1)}$) or zero ($fAPAR_{3(2)}$) at this site. Indeed, the forest floor at Peace River presents almost no green vegetation and could thus have very different spectral properties than the top-of-canopy layer of the primary and secondary canopy layers that are dominated by aspen and green alder, respectively. As for Santa Rosa, the fact that $fAPAR_2$ presented less bias than $fAPAR_3$ (Fig. 4**g-i**) could indicate that measurements of R_{TOC} were not representative for the whole area covered by the WSN. This is supported by the fact that only one measurement of PAR_{TOC} (per tower and sub-site) was carried out - in contrast to multiple sensors for PAR_{soil}. Compared to both other sites, the TDF site presents the highest number of different species. As fAPAR is influenced by both leaf properties and structure (Ollinger, 2011), the higher number of species will increase the variety of geometries, particularly with the occurrence of both lianas and trees (Li et al., 2017b). In addition to that, previous research has shown that lianas present a higher percentage of woody biomass than tree species (Sánchez-Azofeifa et al., 2009), which could lead to a higher spatial variability of R_{TOC}. Thus, one single measurement of R_{TOC} per site, as carried out also in other studies (e.g., Nestola et al., 2017; Senna et al., 2005; Tao et al., 2015), may not be appropriate, particularly in tropical forests. In sum, our findings indicate that adding additional flux terms besides PAR_{in} and PAR_{trans} need to be well-considered. Without proper investigations on spatial variability of R_{TOC} and R_{soil}, there is a risk of introducing a sampling bias (i.e. statistical error) which could hamper the goal of decreasing estimation bias (i.e. systematic error due to assumptions in the radiative transfer equations).

4.2. The role of environmental conditions for the accuracy of fAPAR estimates

The significant effects of season and phenology on the difference between two- and three-flux estimates with the four-flux fAPAR estimate found in the ANOVA (Table 1) are in accordance with previous findings from both simulations with RTMs and field experiments (Putzenlechner et al., 2019a, b; Widlowski, 2010). Particularly, the strong effect of colored leaves found in the mixed-coniferous forest at Graswang (Fig. 6b) is attributed to changes in reflectance properties of beech and maple leaves, as yellow leaves present higher brightness than green leaves, thereby leading to an overestimation bias known from previous investigations (Putzenlechner et al., 2019b; Widlowski, 2010). As $fAPAR_2$ does not consider R_{TOC}, the effect on $bias_{2to4}$ is strongest. Interestingly, the effect is almost as strong for $bias_{3(2)to4}$, for which the corresponding $fAPAR_{3(2)}$ contains the assumption that forest background albedo equals zero. As the effect on $bias_{3(1)to4}$ is much lower, it can be implied that at this site, the approximation of R_{soil} equalizing R_{TOC} for the three-flux estimate is more robust because spectral

Table 1
ANOVA of the bias of fAPAR estimates and environmental conditions at the three study sites; Respective *F*- and *p*-values are shown.

Bias of fAPAR	Graswang				Peace River		Santa Rosa
	Leaf status	Snow	Wind speed	Season	Wind speed	Season	Wind speed
$bias_{2to4}$	17.98***	3.39	3.34	52.27***	102.76***	0.29	112.67***
$bias_{3(1)to4}$	4.81*	1.35	3.86*	28.91***	26.95***	9.29**	38.91***
$bias_{3(2)to4}$	17.88***	3.39	3.34	0.02	8.97**	0.29	31.46***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

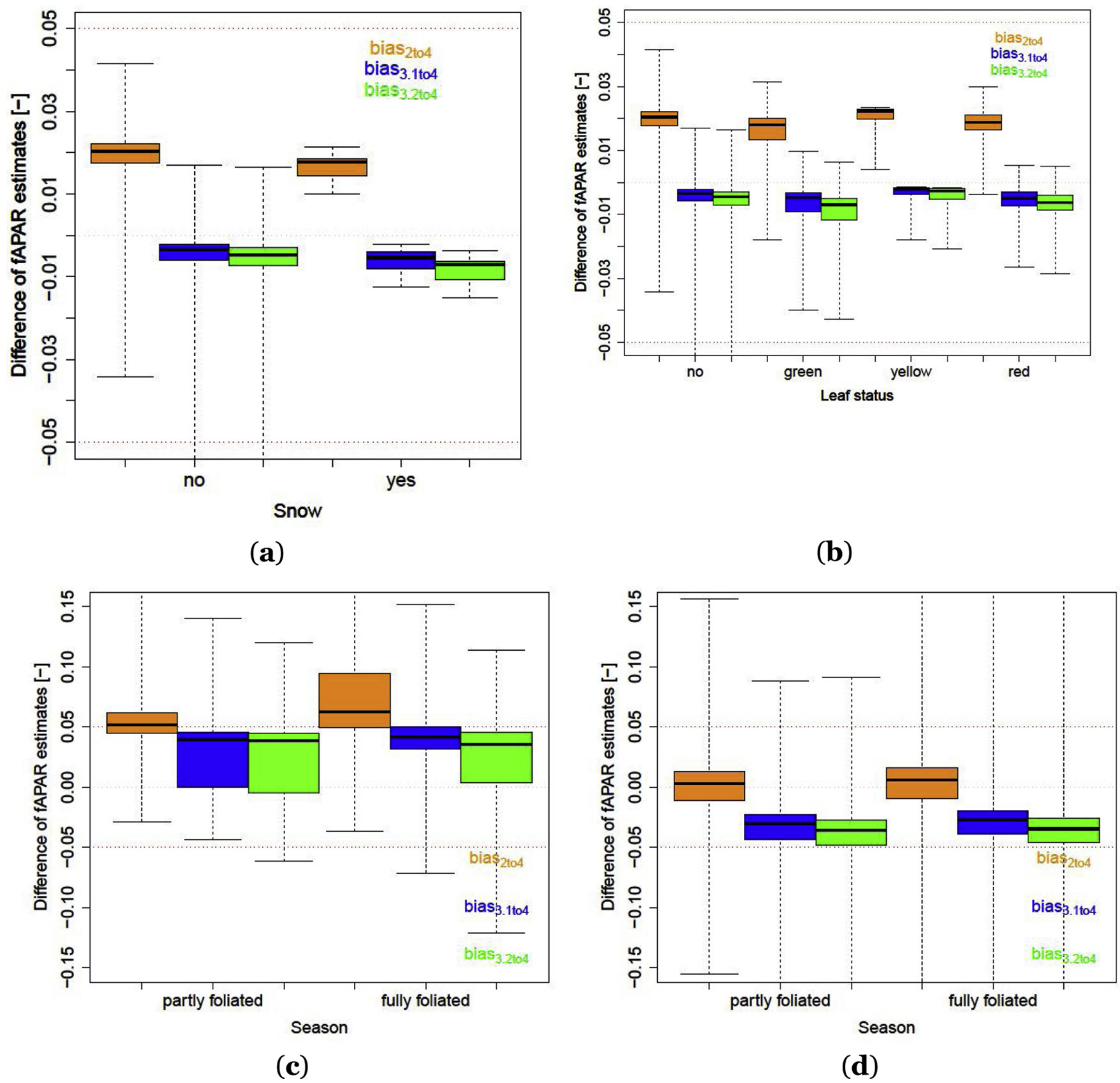


Fig. 6. Bias of fAPAR estimates for various seasonal factors: (**a**) snow and (**b**) leaf status at Graswang; season at (**c**) Peace River and (**d**) Santa Rosa. The dashed red lines indicate the 0.05-uncertainty threshold following the product requirements set by the GCOS (2016). Note that the scale of the y-axis is different for (**a-b**). Only data acquired under low wind speed conditions (i.e., 2 ms^{-1}) is shown. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

properties of the top-of-canopy region and the forest floor were relatively similar at Graswang. This can be explained by the fact that the herbal understory experiences a brown-down as well and (colored) leaves will soon cover the forest floor during senescence period. We found that the factor season had generally stronger effects on the bias of fAPAR estimates at the boreal site than at the TDF site (Table 1). While the boreal deciduous forests of the Albertan aspen parkland are characterized by a short senescence period due to a sharp decline of air temperature in September (Beaubien and Freeland, 2000), TDFs are known for their gradually brown-down which is attributed to progressing drought during dry season (Kalacska et al., 2004). The bright yellow aspen leaves at Peace River will lead to an increase in R_{TOC} which could explain the accuracy decrease of $fAPAR_2$. It should be considered, however, that the strong effect attributed to the factor leaf color and season could be attenuated by effects of low LAI, which has been simulated to lead to a weak underestimation bias of fAPAR estimates (> -0.05) (Widlowski, 2010). Thus, the effect of the factors season and leaf color on the bias of different fAPAR estimates could vary within years, depending on the amount of foliage present during the period of peak color change.

In addition to that, the factor season may also incorporate early snowfalls, which could also have influenced the bias at the boreal site. However, no significant effects on the bias of fAPAR was found during snowy conditions at Graswang, even though simulations with RTMs of previous studies have simulated an underestimation bias for the two- and three-flux estimates (Widlowski, 2010). In previous investigations on the bias of $fAPAR_2$ at this site, it has been suspected that PAR sensors could be affected by snow accumulation (Putzenlechner et al., 2019b). It must be admitted that such uncertainties related to the experimental set-up limit the usage of ground data for validation purposes during the occurrence of snow in forest ecosystems. Nevertheless, it must be considered as well, that the accuracy of satellite-derived fAPAR products may be compromised by effects of spectral mixing between vegetation and snow reflectance values. Even though Widlowski (2010) simulated a strong effect of high forest background albedo on the bias of fAPAR, the meaningfulness of validation studies carried during the occurrence of snow could be questionable in general.

For the factor wind speed, we found significant effects on the bias of fAPAR estimates at the boreal and TDF site (Table 1). Indications for wind speed influencing the uncertainty of two-flux fAPAR estimates have first been discovered at Graswang in previous investigations (Putzenlechner et al., 2019b), even though the influence was also not

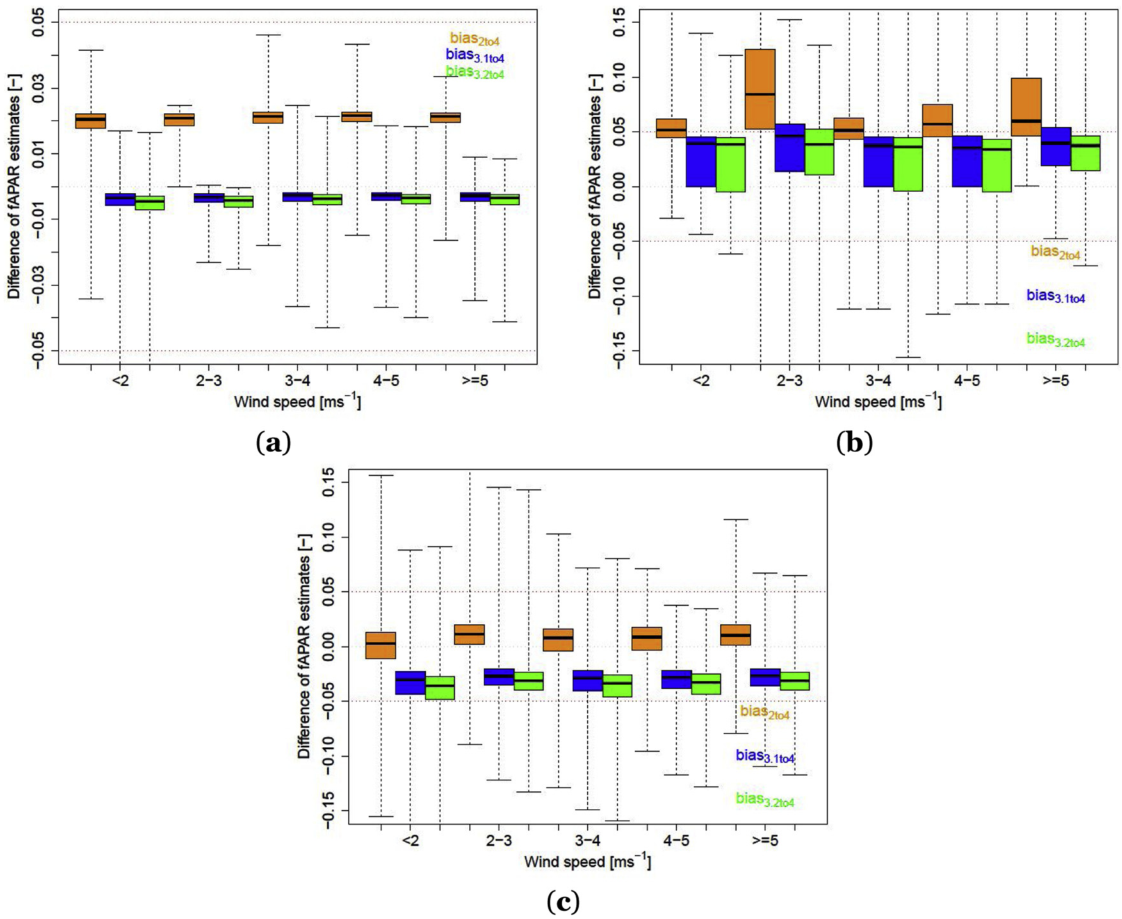


Fig. 7. Bias of fAPAR estimates for different wind speed conditions at (**a**) Graswang (factor leaf status = "green"), (**b**) Peace River (factor season = "fully foliated") and (**c**) Santa Rosa (factor season = "fully foliated"). The dashed red lines shows the 0.05-uncertainty threshold following the uncertainty requirements set by the GCOS (2016). Note that scale of y-axis is different for (**a**). (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

found to be significant. The site's special topographic setting with surrounding mountains giving shelter from high wind speeds compared to the other sites (Appendix B**, Figure B1**) could explain why the effect of wind speed is weak. At Peace River and Santa Rosa, we could see that the effect of wind speed could be attributed mainly to increased R_{TOC} experienced under higher wind speed conditions (Fig. 8). It is well-documented that spectral properties of leaves depend on the vertical position in the canopy (Gara et al., 2018), which are altered with wind

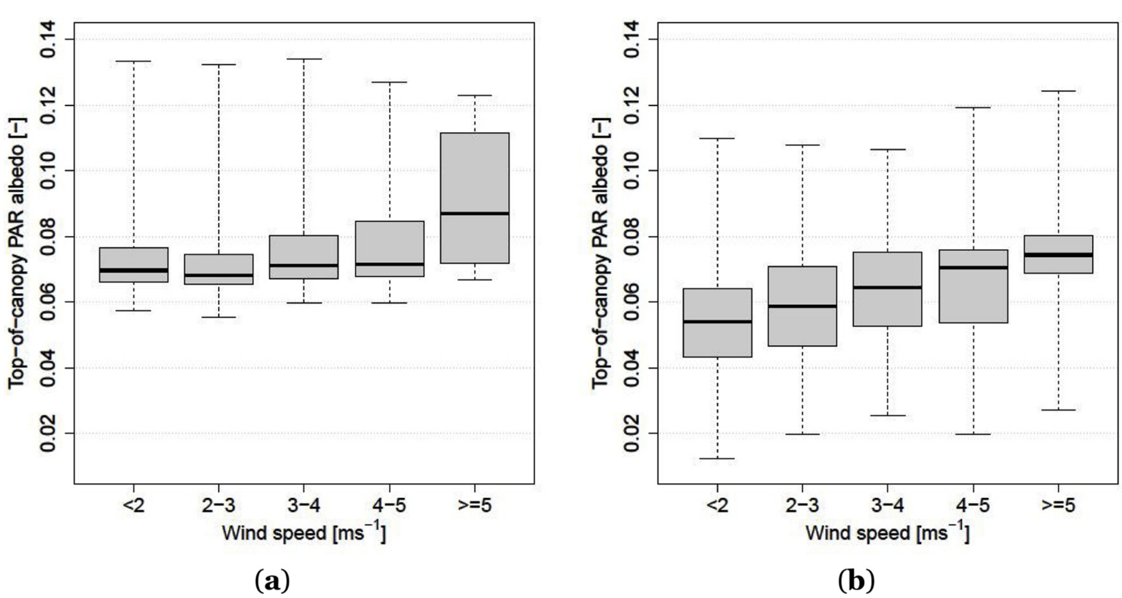


Fig. 8. Top-of-canopy PAR albedo (R_{TOC}) acquired under different wind speed conditions during fully foliated season at (**a**) Peace River and (**b**) Santa Rosa.

speed conditions. Exceeding the 0.05-uncertainty threshold also during lower wind speeds at the boreal site ($bias_{2to4}$ for $2-3\,ms^{-1}$, Fig. 7b) coincides with the highest frequency of wind speed conditions (Appendix B, **FigureB1**) and thus shows the general disadvantage of the two-flux fAPAR estimate at this site. In fact, trembling aspen, the dominating species at Peace River, are named after their characteristic leaf flutter already during low wind speed conditions (Gara et al., 2018). The fluttering of the top-of-canopy leaves (often referred to as "sun leaves") creates uniform photon flux densities so that incoming PAR is distributed in the canopy regardless of variation in leaf orientation and solar position (Roden, 2003). Consequently, the effect of wind speed on the bias of fAPAR was highest at Peace River and in addition to that crossed the GCOS uncertainty requirements (Fig. 7b). Based on our findings, we therefore recommend opting for three-flux fAPAR estimates at sites that frequently experience higher wind speeds.

4.3. Evaluation of the methodological approach for the bias assessment

Despite these distinct findings on the performance of different fAPAR estimates from our study we must discuss limitations of our approach in terms of 1) the experimental approach itself and 2) its context of using in situ fAPAR estimates to validate satellite- derived fAPAR products. Regarding 1), it should be considered that the four-flux fAPAR estimate was assumed to be closest to the truth. While ignoring the contribution of horizontal PAR fluxes was found to be problematic only for small experimental sites (Widlowski et al., 2006), this estimate could still be affected by horizontal fluxes. In this regard, SZA is a potential source of bias, that was not investigated as pyranometers required to classify fAPAR timesteps according to the ratio of diffuse-to-direct incoming radiation were not available at all the sites. Previous research at the temperate site has shown that during high SZAs, the bias of the two-flux fAPAR estimate exceeded 0.05 fAPAR units (Putzenlechner et al., 2019b). However, there is currently no experimental technique developed for quantifying horizontal fluxes with commercially available hemispherical PAR sensors as used in this study and it could thus be interesting to investigate the bias of the four-flux fAPAR estimate with spherical PAR sensors, as applied by Leuchner et al. (2011) in an ecological context (i.e., PAR radiation as a driver for competition). Finally, another limitation of the four-flux fAPAR estimate represented the restriction to meteorological conditions (i.e., clear sky, calm air) at the site Graswang with the UAV approach, resulting in only several estimates of R_{TOC} which showed considerable variability.

In the context of using fAPAR estimates for validating satellite-derived fAPAR products, underlying fAPAR definitions should be considered. In contrast to satellite-derived fAPAR products, which mostly relate to "green" fAPAR (Gobron, 2015), PAR sensors measure "total" fAPAR, referring to the PAR absorption of both green and non-green vegetative elements (Gobron, 2015). Authors of existing studies have stated that the exact contribution of such bias is difficult to quantify, but could be below 10 % (Nestola et al., 2017; Zhang et al., 2013). The bias between "total" and "green" fAPAR could be particularly high at the tropical site, as liana species are known for their higher ratio of woody biomass (Sánchez-Azofeifa et al., 2009). Given the facts that recent studies have raised attention on discrepancies of satellite-derived fAPAR products in tropical forest regions (Xiao et al., 2018; Xu et al., 2018), we see the need for future investigations on the bias between "green" and "total" fAPAR especially in tropical forests. Investigating the bias between "green" and "total" fAPAR could be done by evaluating direct fAPAR measurements with DHPs at the sensor locations or by the means of in situ RTM simulations. Another issue related to different fAPAR definitions is that our measurements were acquired during all illumination conditions. In future bias investigations, a clear differentiation into "black-sky" and "white-sky" fAPAR would be favorable for improving the comparability to satellite-derived fAPAR products, which mostly relate to "black-sky" fAPAR (Gobron, 2015). In return, we welcome satellite-derived fAPAR products based on retrieval algorithms for both "white-sky" and "black-sky" conditions as recently proposed by Liu et al. (2019) as an important step towards an improved comparability of fAPAR maps and ground measurements.

Nevertheless, our investigations have provided the first insights into the accuracy of different fAPAR estimates varying with ecosystem type and environmental conditions based on direct PAR measurements which we consider beneficial for the implementation of sampling protocols in the context of validation activities of satellite-derived fAPAR products.

5. Conclusions

This study presented an assessment on the differences and uncertainties of different fAPAR estimates at three forest sites: a conifer-dominated forest in Southern Germany, a boreal-deciduous forest in Northern Alberta at the Peace River Environmental Monitoring Super Sites, Canada and a tropical dry forest (TDF) at the Santa Rosa National Park Environmental Monitoring Super Site, Costa Rica. Based on permanent measurements with Wireless Sensor Networks (WSNs) of incoming, transmitted PAR as well as PAR albedos of the top-of-canopy region and the forest floor, we performed two-, three and four-flux fAPAR measurements, depending on the number of flux terms considered. As four-flux fAPAR considers the highest amount of flux terms to describe the canopy absorption in the PAR domain (i.e., only horizontal PAR fluxes are ignored), we assumed this quantity closest to "true fAPAR". Thus, to evaluate the uncertainty of two- and three-flux estimates, we calculated their differences with the four-flux estimate and referred to this quantity as bias. As the bias of a certain fAPAR estimate is known to vary with environmental conditions, we assessed the influence of several environmental conditions with multifactorial ANOVAs.

In our analysis, we were particularly interested whether bias of certain fAPAR estimates fulfill the 0.05-uncertainty threshold following the product requirements set by the GCOS (2016). In this regard, we found that the highest average biases of different fAPAR estimates accounted to 0.02 at the temperate site, 0.08 at the boreal site and -0.05 at the tropical site. Thus, the uncertainty requirements set by the GCOS (2016) were fulfilled at the temperate and tropical site. At all three sites, the two-flux fAPAR estimate was found to consistently overestimate the four-flux fAPAR estimate. It is important to stress, however, that the three-flux fAPAR estimates, which have been favored frequently in previous studies, were not found to necessarily reduce overall bias, especially at the tropical site. We argued that higher bias of the three-flux estimates could arise from non-representative measurements of R_{TOC} due to higher number of tree species and thus higher spatial variability of fAPAR in the TDF forest. Concerning the influence of environmental factors referring to seasonal and phenological changes, such as bright colored autumn leaves, we found significant influences on the bias of fAPAR. The effect was considerably pronounced for the two-flux fAPAR estimate at the temperate and boreal sites, even though uncertainty requirements remained fulfilled. A significant effect of higher wind speed conditions on the bias of two- and three-flux estimates was found at the boreal and TDF sites. This effect was found to be mainly attributed to increases in the top-of-canopy albedo during higher wind speeds. At the boreal site, the absolute bias of the two-flux fAPAR estimate exceeded the 0.05-uncertainty threshold already during lower wind speed conditions. Based on our findings, the following conclusions could serve as practical recommendations for planning future experimental set-ups with direct PAR measurements, aiming at validating satellite-derived fAPAR products:

1 The bias of two-flux fAPAR observations, which are relatively cost and labor efficient, is bearable under typical summer conditions (i.e. green leaves, no snow, low wind speed).
2 At sites with frequently higher wind speed conditions, at least three-flux observations (better four-flux) should be carried out.

3 At sites where top-of-canopy albedo can be expected to differ considerably from forest background albedo (e.g., due to different species composition or fractional cover), an approximation of forest background albedo with top-of-canopy albedo in the three-flux estimate should be avoided as this approximation will increase the bias compared to two-flux estimate; in this case, top-of-canopy albedo should either be approximated with zero or measurements of forest-background albedo should be carried out so that the four-flux fAPAR estimate can be calculated.
4 To reduce statistical errors (i.e. sampling bias), multi-sensor approaches as possible with WSNs should be favored not only for measurements for transmitted PAR, but also for PAR fluxes reflected from the top-of-canopy region as well as the forest floor. In this regard, forests with high diversity of plant species will require special attention.

In sum it has been demonstrated that WSNs serve for assessing the bias of different fAPAR estimates which is needed for developing transparent sampling protocols for in situ fAPAR observations. Overall, investigating the bias of fAPAR in very different forest ecosystems allows the conclusion to be drawn that two-flux fAPAR observations present a good compromise between accepting uncertainties involved under specific environmental conditions and providing permanent fAPAR datasets suitable and urgently needed for the validation of satellite-derived fAPAR products.

Declaration of Competing Interest

The authors declare no conflict of interest.

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CRediT authorship contribution statement

Birgitta Putzenlechner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing - original draft. **Philip Marzahn:** Project administration, Resources, Methodology, Writing - review & editing. **Arturo Sanchez-Azofeifa:** Data curation, Project administration, Resources, Supervision, Writing - review & editing.

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Appendix A. Supplementary data

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