Sentinel satellite-based mapping of plant productivity in relation to snow duration and time of green-up (GROWTH)

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Keywords: Sentinel-1, Sentinel-2, FLOX, snow, phenology, plant productivity

1. Introduction

Plant productivity (g biomass / m^{2}*y) is fundamental to Arctic tundra ecosystem's functions and services. Annual plant production is vital for wildlife, it plays a key role in the global carbon budget, nutrient cycling, surface energy budget and large-scale climate. However, measuring plant productivity is a challenging task. Carrying out long-term field-based studies of plant productivity is labour intensive, and only few time-series exist for the Arctic. On Svalbard, the only long time-series of field-based measurements is from Semmeldalen on Nordenskiöld Land peninsula (van der Wal and Stien 2014). Satellite image-aided analysis of plant productivity provides a method for determining spatially complete coverage that can be used to interpolate traditional ground-based estimations of biomass and production. Several remotely sensed Normalised Difference Vegetation Index (NDVI) based studies covering large areas of northern high latitudes indicate increased vegetation greenness during the last few decades (Myneni et al. 1997; Epstein et al. 2013; Xu et al. 2013; Park et al. 2016; Vickers et al. 2016), but with mostly less increase or even regionally a decreasing trend since approximate the millennium shift (Bhatt et al. 2013). However, only a few of these large-scale studies (Epstein et al. 2012, Raynolds et al. 2012) have used extensive plant biomass data for validation, and then only data from one season, not catching the annual variation. Additionally, Guay et al. (2014), who used mean NDVI for June-August to investigate trends from different satellite datasets (e.g. MODIS, Spot Vegetation, and different versions of the GIMMS dataset), showed that temporal trends were highly dependent on the dataset used. Each year the NOAA Arctic Report Card is presented, showing the research on Arctic tundra vegetation dynamics from the previous year (Epstein et al. 2018). But most of the observations therein are linked to satellites with coarse spatial resolution. However, in Svalbard, the field data from Semmeldalen (van der Wal and Stien 2014) were linked to a time-series of clear-sky MODIS satellite data for the 2000-2014 period (Karlsen et al. 2018) and referred to in the Arctic Report Card (Epstein et al. 2018). This regional study (covering Nordenskiöld land) also utilizes phenological maps showing onset of growth (Karlsen et al. 2014), and showed that the best fit between field data and MODIS data was with time-integrated NDVI from onset to peak of the growing season. This study revealed large differences between years in plant production, a strong link to summer temperatures, and a possible link to sea-ice distribution (Macias-Fauria et al. 2017). However, only relative differences in the spatiotemporal pattern of plant production were found, partly due to the coarse resolution of MODIS data (250x250m^{2}). Hence, there is a need to develop methodologies to map actual plant productivity in terms of grams of biomass per square meter per year (g / m^{2}*y). With the new generation of satellite data, in particular Sentinel-1 and Sentinel-2 data, we have frequent coverage combined with high spatial and spectral resolution, allowing us to work at the plant community level. In addition, automatic field and near-field sensors and cameras for ecological monitoring have become cheaper and with higher capacity and more capabilities in recent years.

In this State of Environmental Science in Svalbard (SESS) report, we show different datasets, Svalbard Integrated Arctic Earth Observing System (SIOS) based and others, in the Adventdalen valley area, close to Longyearbyen, which can be linked and utilized in plant productivity measurements. Further, Svalbard is undergoing dramatic climatic changes, with periods of heavy rain instead of steady snow cover in autumn, and mild periods in mid-winter creating ice or even snow free spots have occurred several times in the last years (Bjerke et al. 2017). How these extreme climatic events and changes in snow duration, snow properties, and time-of-green-up affect the plant growth is largely unknown at the plant community and ecosystems level, and there is a need to provide more accurate proxies of plant productivity at large spatial scales. Clearly, there is a valuable opportunity for developing methodologies that combine field-based measurements and near ground sensors of plant productivity with Sentinel data in order to validate satellite data and provide more accurate estimates of plant productivity at different spatial scales.

2. Overview of existing data

Several SIOS-based and other datasets located in Adventdalen, close to Longyearbyen, can be combined in measuring plant productivity and to detect climatic drivers. The datasets are both satellite data (Sentinel) and from field-based measurements/near ground sensors.

2.1 Satellite data

2.1.1 Time-series of Sentinel-1 data

The instrument #42 (Snow parameter retrieval using remote sensing satellites) belongs to the cryosphere module of the project SIOS-InfraNor[1]. We have pre-processed Sentinel-1 Ground Range Detected (GRD) data from the interferometric wide swath mode (10 m pixel spacing) HH and HV polarization over Nordenskjold land. The time series started in 2015 with a few scenes, and gradually increased to regular 2 scenes per 6 day repeat cycles in 2018. Figure 1 shows a composition of three backscatter Sentinel-1 images in the HV channel, corresponding to different periods of the year 2018 (March, May and July). Sentinel-1 also provides Extended Wide Swath data (40 m pixel spacing) but this product will be considered later. C-band SAR (5.6 GHz) is only sensitive to wet snow. Wet snow maps can thus be provided on a regular basis (2.3 scenes per week) independent of cloud conditions. This is a big advantage in contrast to optical data like Sentinel-2 which require cloud-free conditions. In addition to wet snow, C-band SAR data can also provide indications of thawing/freezing conditions in the active permafrost layer and on the soil

1 https://sios-svalbard.org/InfraNor

moisture.

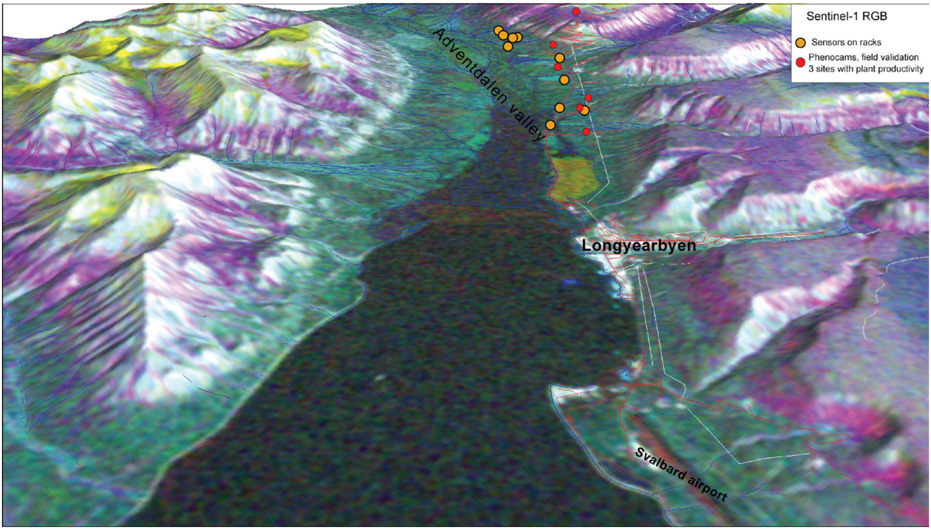

Figure 1: RGB composition of three Sentinel-1 HV images from Adventdalen: 1 March 2018 (red), 29 July 2018 (green), 30 May 2018 (blue). The colours identify patterns in the surfaces, deriving from the different backscattering mechanisms. The dark blues and blues across the figure represent low-changing features such as the sea or the airport, the green colours the vegetated areas, the purple represents bare soil or rocks, while yellow features surfaces, which are affected by major variations, i.e. wet snow in July.

2.1.2 Time-series of clear-sky Sentinel-2 data

Within the SIOS-InfraNor instruments # 52 (Time-series of medium resolution satellite data) time-series of clear-sky Sentinel-2 (S2) are processed. Due to the northern location S2 data are obtained almost daily, and with Sentinel-2B data in addition from July 2017, often twice a day. The data covering Adventdalen are obtained between approximate 11:30 and 13:30 UTC. Frequent fog and clouds, snow and ice, a short growing season, and often weak response from the vegetation characterize Svalbard, and make cloud masking on the archipelago a challenging task. The cloud detection provided with the bottom-of-atmosphere Sentinel-2 product (L2A) often fails and is of limited value. In particular, detection of shadows from cloud, clouds over sparsely vegetated areas, thin clouds, and shadows from cirrus often fails. In processing clear-sky time-series we combined several methods, included visual quality control. For most of the images used, we manually masked out the cloudy parts by drawing polygons around them, using several different cloud-detection algorithms to aid this work, depending of the cloud type and time of season. This is time-consuming work, but it is only done once and ensures that most of the noise in the datasets is removed and that most (>80%) of the noise-free data are retained. All Nordenskiöld Land will be processed for the years 2016-2018 for the period late April to late September. For this late April to late September period for the Adventdalen valley floor, the results show 12-15 cloud-free days in 2016, 16-22 days in 2017, and 15-21 days in 2018. However, the days were not evenly disturbed throughout the season, and fewer cloud-free days were obtained in the surrounding mountains. Next the cloud-free pixels were interpolated to daily data. For the indices NDVI and Normalised Difference Snow Index (NDSI) a Kernel Ridge Regression machine learning method was used for interpolation, combined with Savitzky-Golay filtering. In most cases the processing of S2 data to bottom-of-atmosphere (L2A) worked, however, in some images errors were found in terrain correction or in atmospheric correction. The reason for this needs further investigations. Due to the limited cloud-free days available, we have so far only used top-of-atmospheric data (L1C), since removing the L2A products with errors will further decrease the number of days with cloud-free data. From this clear-sky time-series of daily NDVI/NDSI data we extracted the last day of snow cover, onset of growth (Figure 2) and time-integrated NDVI from onset to peak of the season (OP NDVI) (Figure 3). The OP NDVI data indicate annual plant production but needs further validation with the field data and near-ground sensors/camera data to obtain gram living green biomass per square meter per year.

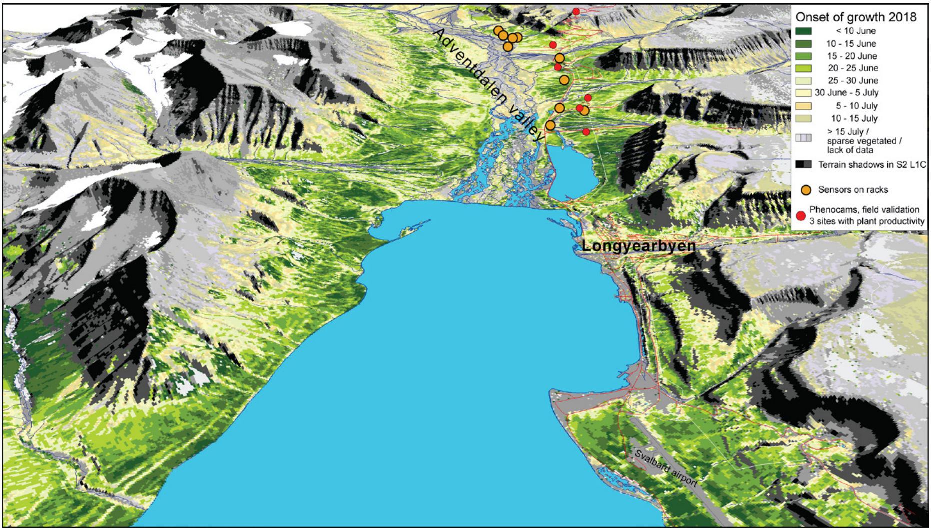

Figure 2: Onset of the growing season for the year 2018. Extracted from time-series of clear-sky Sentinel-2 NDVI data.

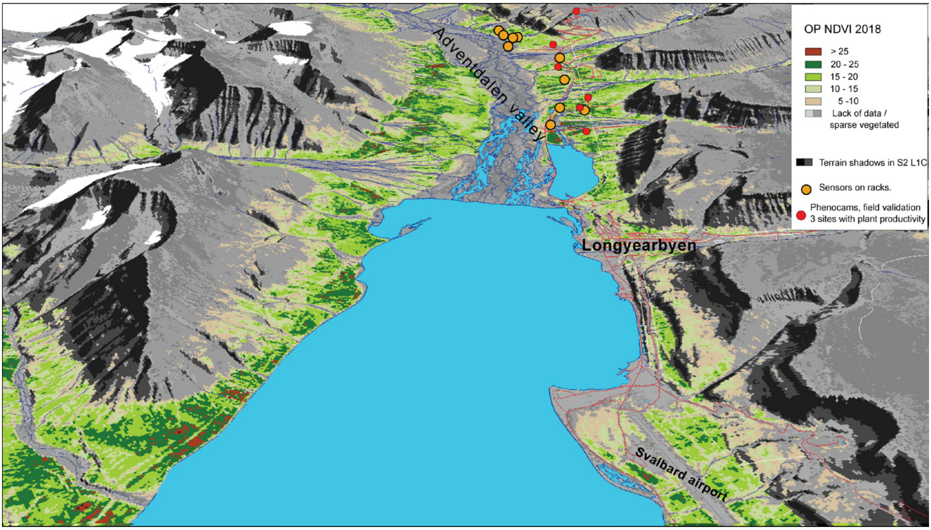

Figure 3: Time-integrated NDVI from onset of growth to peak of growth (OP NDVI) for the year 2018. Extracted from time-series of clear-sky Sentinel-2 NDVI data. The values indicate the annual plant productivity, but need to be validated from in-situ data.

2.2 Field data and near-ground remote sensing data

2.2.1 Imaging and non-imaging sensors on racks

SIOS-InfraNor Instrument #44 is an automatic system for monitoring vegetation and environmental seasonal changes (phenology) on Svalbard (AsMovEn). Ten racks and three landscape cameras are distributed within the lower part of Adventdalen. The racks have basic equipment comprising one Red-Green-Blue (RGB) camera, non-imaging NDVI and photochemical reflectance index (PRI)-sensors and a sensor measuring both soil moisture and temperature. In addition, some have additional equipment like a thermal infrared sensor measuring surface temperature and a sensor recording the PRI. For calibration purposes, hemispheric NDVI and PRI sensors were mounted on some racks measuring incoming radiation. Retrieval of greenness indices like GRVI (Green-Red Vegetation Index) and NDVI showed that these indices successfully recorded timing of the green-up and plant growth periods and senescence in all six plant species/groups in the period 2015-2018, and the first year is reported (Anderson et al. 2016). Figure 4 shows NDVI versus surface temperature from the end of April to the beginning of October 2017 from one of the racks. Data were recorded in the Arctic bell-heather (*Cassiope tetragona*) heath on the lower part of an alluvial fan.

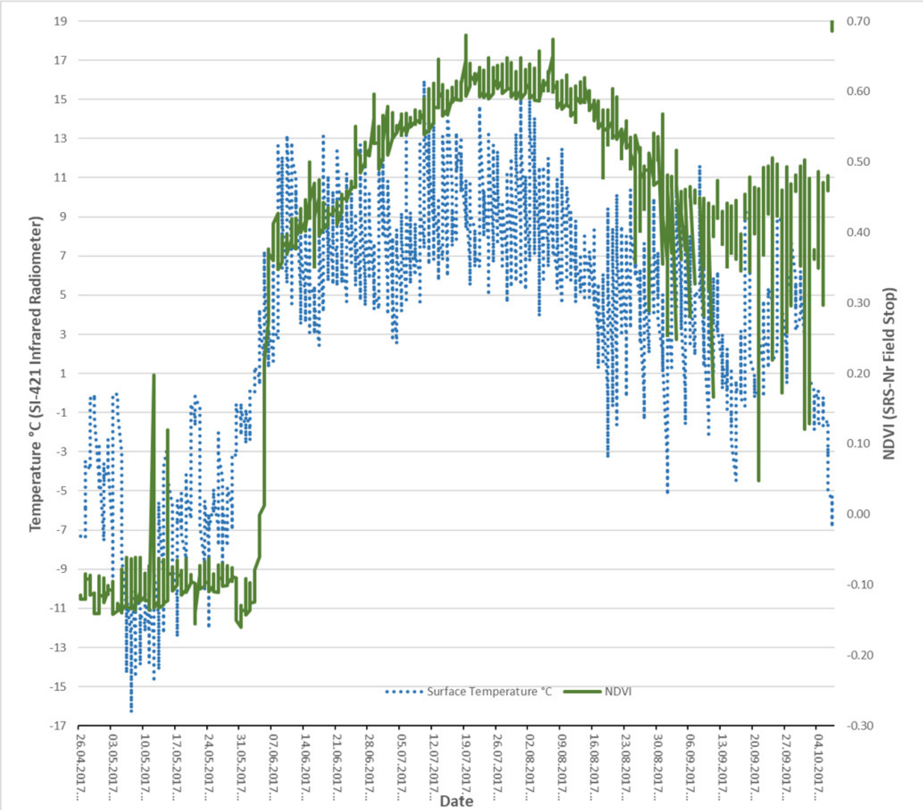

Figure 4: Example of selected data from one of the ten racks in Adventdalen. Plot showing NDVI versus surface temperature as measured by the infrared radiometer in heath vegetation (*Cassiope tetragona- Dryas octopetala* type) for the 2017 season.

2.2.2 Sun-Induced measurements by the spectroscopy system FLoX

SIOS-InfraNor instrument #49 (FLoX), is a state-of-the-art spectrometer that measure Sun-Induced Fluorescence (SIF), which is a new global proxy for GPP (Gross Primary Production). The instrument was established in Adventdalen in beginning of June 2019. Passive Sun-induced chlorophyll fluorescence (SIF) is a radiation flux emitted by chlorophyll molecules in the red (RSIF) and far red region (FRSIF) and provides a better direct proxy for photosynthesis independent of ancillary information or modelling steps which is needed by other methods (Yang et al. 2015). SIF occurs as a direct result of light absorption by the chlorophyll complex during photosynthesis (Porcar-Castell et al. 2014). SIF can be acquired from ground- and satellite-based observations (Yang et al. 2015, Frankenberg et al. 2014) like the FLoX-instrument established close to and within the foot print of the Eddy-Covariance tower (Pirk et al. 2017) in Adventdalen (Figure 5). The eddy covariance technique (EC) is a widely used atmospheric measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers and determine exchange rates of trace gases (like CO_2 and methane) and hence the net ecosystem exchange of CO_2 (NEE) over agricultural lands and natural ecosystems (Pirk et al. 2017). The SIF-measurements acquired by the FLoX-system on the ground and similar systems are good proxies for EC-measurements and will become important ground calibration sites for satellite-based systems.

Figure 5: Sun-Induced measurements by the spectroscopy system FLoX. The FLoX-system (foreground) is established near and within the footprint of the Eddy-Covariance station (in background) in Adventdalen (Photo: Lennart Nilsen).

The FLOX (JB Hyperspectral Devices, Düsseldorf, Germany) is a field spectrometer designed for continuous and long-lasting high-resolution spectral measurements of radiances and for SIF retrieval at the top-of-canopy. The spectrometer technical specifications in terms of spectral coverage, resolution and signal-to-noise (SNR) were designed based on the FLEX mission instrument specifications (Drusch et al. 2017, Coppo et al. 2017). The FLOX is equipped with two grating spectrometers: (i) QEPro (Ocean Optics, Largo FL, USA) with high spectral resolution (FWHM~0.3 nm; SSI~0.15 nm) in the fluorescence emission range

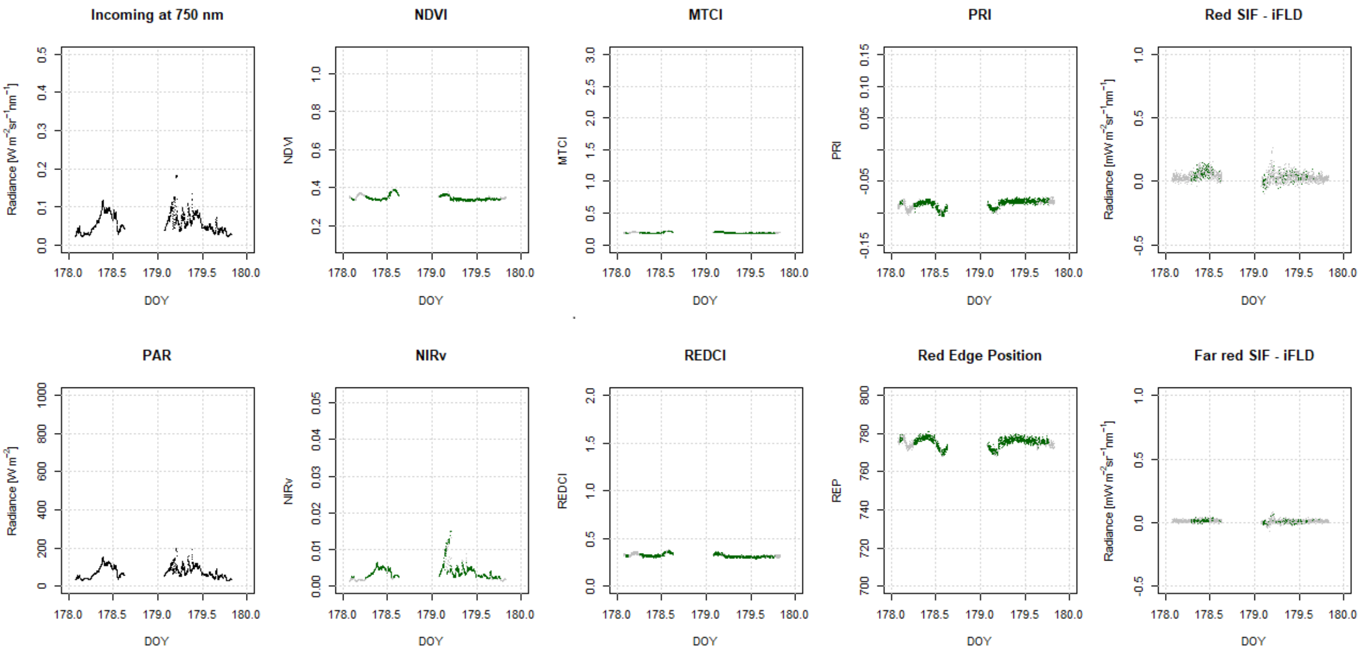

Figure 6: Measurements by the spectroscopy system FLoX during Day no: 178 and 179 in June 2019. NDVI: Normalized Difference Vegetation Index; MTCI = MERIS terrestrial chlorophyll index; PRI= Photochemical Reflectance Index; PAR: Photosynthetic Active Radiation, NIR_V: Near Infrared Reflectance of terrestrial vegetation (the product of total scene NIR reflectance NIR_T) and NDVI; REDCI: between 52S and 52N; Red Edge position: Results are reported as the wavelength of the maximum derivative of reflectance in the vegetation red edge region of the spectrum in microns from 690 nm to 740 nm; and the Sun-Induced fluorescence measurements at Red: and Far red: used the FLD-method.

650 nm–800 nm; (ii) FLAME S (Ocean Optics, Largo FL, USA) covering the full range of VIS-NIR (FWHM~1.7 nm; SSI~0.6 nm). The spectrometer's entrance is split towards two optical fibres that lead to a cosine receptor measuring the downwelling radiance and a bare fibre measuring the canopy upwelling radiance.

Preliminary results on only few data from the growing season 2019, indicate that the calibration of the data remained good during the cold Svalbard weather conditions. Since 2019 is considered to be a test season, this is encouraging. Figure 6 shows various parameters and indices that can be extracted from the FLoX-measurements like that the chlorophyll content (MTCI) was rather low but changing during the growing season. SIF was very low and could be explained by low incoming radiance and low chlorophyll content of the vegetation (Figure 6). In the limited processed data, Vegetation Indices (Vis) are not showing strong daily dynamics, since the VIs like the NDVI are not directly related to physiological changes. Usually these VIs are affected by directional effects (Bidirectional Reflectance Distribution Functions (BRDFs) and change during the day according to the sun position and sun angle. In the data processed, most of the time it was cloudy, so light was mainly diffuse light, in this case the directional effect would have less important effect on the results. The FLoX-measurements of SIF may provide better estimates of start and end of the growing season across the Arctic regions than the satellite-derived vegetation indices like Enhanced vegetation Index (EVI) and NDVI (Luus et al. 2017). They found that the EVI-based seasonality measure indicates that spring "green-up" occurred 9 days prior to SIF-based estimates, and that the SIF-based estimates agreed with aircraft and carbon-flux tower measurements of CO_2. Further analysis will be run when the dataset from the whole growing season 2019 (June-September) is retrieved.

2.2.3 Phenocams

In order to monitor plant phenophases in field, eight to nine phenocams (trail cameras, mainly type LTL Acorn) were used in the Adventdalen for the 2014-2019 period (Figure 7). The placement of the cameras was designed to be up-scaled to the resolution of Sentinel-2 data.

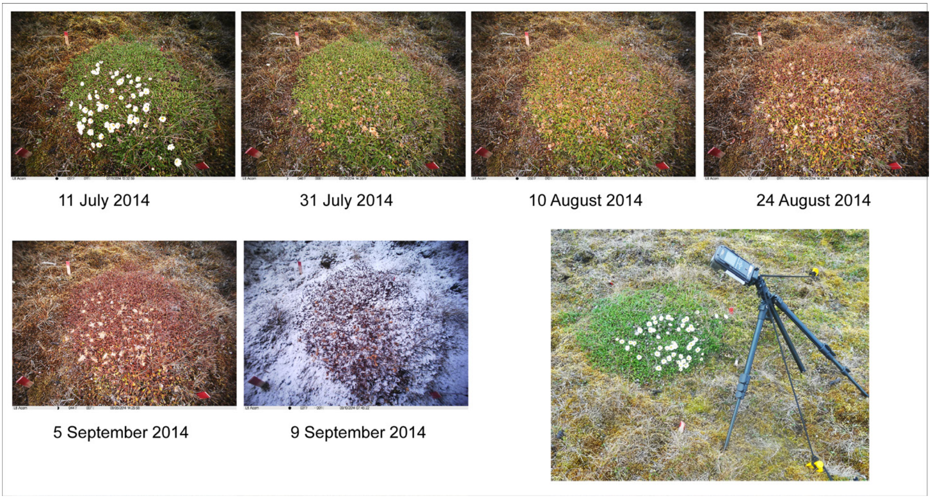

Figure 7: Eight or nine cameras in Adventdalen have been used since 2014 to document plant phenology. The example shows selected images of mountain avens (*Dryas octopetala*) for the July to September 2014 period.

2.2.4 Field measurements of plant productivity

Annual field measurements of plant productivity were collected from tundra-grass (*Dupontia fisheri*) and woodrush (*Luzula confusa*) in the Adventdalen valley area (Stendardi and Karlsen 2016). About 1600 measurements of the length of leaves were done annually for the 2015 to 2019 period. The measurements are from five sites, two on tundra-grass and three on woodrush. The sites were selected where the species was dominant and covered large enough area for up-scaling to Sentinel data. The results show annual biomass (g / m^{2}*y) measured on 18 x 18 cm^2 plots with 100% plant cover, up-scaled to 1 x 1 m^2 (Figure 8). The sites have some co-location with phenocams and the sensors on racks. The measurements were done by The Free University of Bolzano, Italy, in cooperation with NORCE.

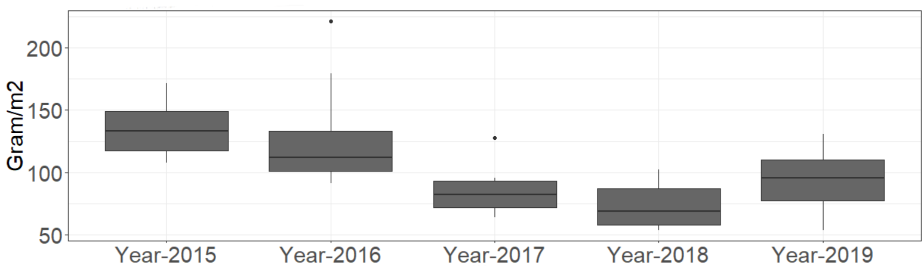

Figure 8: Example of annual plant production measured on the ground on woodrush (*Luzula confusa*) in the Adventdalen valley. Squares of 18 x 18 cm^2 with 100% plant cover is measured and up-scaled to 1 x 1 m^2.

2.2.5 Other data

A carbon flux tower with adjacent automatic flux chambers is installed in Adventdalen, belonging to Lund University (P.I. Torben Christensen, currently with Aarhus University). The measurements have been discontinued the last few years but there is potential for collecting valuable data on carbon fluxes and gas emissions from the tundra vegetation. Multispectral sensors (Skye non-imaging radiometers) exist but are not yet installed.

2.2.6 Connection to other SIOS work

The satellite data and field measurements in Adventdalen presented here have connections and synergies with other work presented in this issue. The chapter 'The Environmental Monitoring in the Kapp Linné-Grønfjorden Region' (Retelle et al. 2020) includes some related ecological work. The Adventdalen observation work has an obvious synergy to the chapter 'Climate-Ecological Observatory for Arctic Tundra' (Pedersen et al. 2020), and their study of the food web. The active-layer thickness impacts the vegetation and the Adventdalen observations presented here, have a connection to the chapter 'Permafrost thermal snapshot and active-layer thickness in Svalbard 2016-2017' (Christiansen 2020).

3. Unanswered questions

- For which species and plant communities and with what accuracy can plant productivity be measured with the available data in Adventdalen?
- What is the best ground-image resolution and which spectral features provide the best time-serial data for recording plant species phenology and productivity?
- How can we combine and analyse data through different spatial scales from field data, and near ground sensor data to Sentinel data? Can information on plant productivity from one scale explain pattern observed at larger scales?
- How do we measure bryophyte annual productivity, on the ground, with near ground sensors, and with Sentinel data?
- How do we identify and measure climatic drivers for plant productivity on the scale of plant communities?
- What is the diurnal (day and night) pattern of photosynthesis as measured by SIF?
- What is the growing season variation in measured environmental parameters, SIF and vegetation indices (VIs)? And how does the low sun elevation on Svalbard influence these parameters?

4. Recommendations for the future

- There is a need for developing methodologies that combine field-based measurements and near ground sensors on plant productivity with Sentinel data in order to validate satellite data and provide more accurate estimates of plant productivity at large spatial scales.
- There is a need to determine how the NDVI-sensor data relate to plant productivity data in order to quantify productivity as gram per square meter per year (g / m^{2}*y).
- There is a need for a detailed Sentinel-based vegetation map covering larger part of Svalbard in order to up-scale from the Adventdalen area.
- There is a need for a more detailed study of the effects of bryophytes upon remote sensed vegetation indices in order to analyse their contribution to both the spatial and temporal patterns of vegetation development. This should include plant productivity measurements on moss-tundra (preferably *Tomentypnum nitens - Aulacomnium turgidum* type), on sites which can be up-scaled with Sentinel data.
- There is a need to develop methods to use the FLoX-measurements, and especially SIF measurements, as calibration for different ongoing and coming satellite sensor systems. This includes studies on how FLoX-measurements can act as valuable proxies for photosynthesis and carbon fluxes at present time and in the future, and to study how the SIF measurements both from surface (FLoX) and space can be used for better detection of the start, peak and end of the growth season.

5. Data availability

Table 1: Different datasets, SIOS based and others, in the Adventdalen valley area, close to Longyearbyen, which can be linked and utilized in plant productivity measurements.

Data	Description	Provider, data access
Time-series of Sentinel-1 data	SIOS-InfraNor instrument #42 (Snow parameter retrieval using remote sensing satellites),	NORCE Technology. Will be on server by early 2020. Contact: Eirik Malnes.
Time-series of Sentinel-2 data	Time-series of cloud-free Sentinel-2 data (SIOS-InfraNor instruments # 52) covering Nordenskiöld Land for the period 2016-2018	NORCE Climate. Will be on server by early 2020. Contact: Stein Rune Karlsen.
FLoX	SIOS-InfraNor instrument #49 (FLoX). The FLoX is a spectroscopy system for the unsupervised retrieval of Sun-Induced-Fluorescence (SIF) and spectrally resolved reflectance.	Norwegian Institute for Nature Research (NINA). Contacts: Hans Tømmervik (NINA) and Lennart Nilsen (UiT)
Imaging and non-imaging sensors on rack	SIOS-InfraNor instrument #44. Establishment of an automatic system for monitoring vegetation and environmental seasonal changes on Svalbard. Ten racks and three landscape cameras are distributed within the lower part of Adventdalen.	The Arctic University of Norway. Contact: Lennart Nilsen.
Plant production measurements	Plant productivity measurements on two graminoides at 6 sites in Adventdalen. Annual measurements from 2015 to 2019.	Faculty of Science and Technology, Free University of Bozen-Bolzano, Italy. Contact: Laura Stendardi.
Phenocams	Eight to nine phenocams cameras in Adventdalen observing phenology. One photo each hour from 10am to 3pm, from early June to early September for the 2014-2019 period.	NORCE Climate. Contact: Stein Rune Karlsen.

Acknowledgements

This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC).

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