EO Africa // ARIES

D18 – Potential and Limitations for CHIME and LSTM (Report)

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ABSTRACT:

This document describes the assessment of the developed analysis techniques potentials and limitations with respect to future ESA missions (CHIME and LSTM)

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List of Acronyms

AKTC	Zambian Agricultural Knowledge and Training Centre, LTD
BOA	Bottom of Atmosphere
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
ECOSTRESS	Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
EnMAP	Environmental Mapping and Analysis Program
EO	Earth Observation
ERA	European Centre for Medium-Range Weather Forecasts atmospheric reanalysis
ESI	Evaporative Stress Index
ET	Evapotranspiration
EU	European Union
LST	Land Surface Temperature
LSTM	Copernicus Land Surface Temperature Monitoring
MODIS	Moderate Resolution Imaging Spectroradiometer
NDWI	Normalized Difference Water Index
PRISMA	PRecursore IperSpettrale della Missione Applicativa
SAlib	Sensitivity Analysis Library
SBG	Surface Biology and Geology
S3	Sentinel-3
TRISHNA	Thermal InfraRed Sensor for High-resolution Natural resource Assessment
STR	Shortwave Infrared Transformed Reflectance
UTC	Coordinated Universal Time

1 Introduction

Altogether six Sentinel Expansion missions are currently being developed to address EU policy and gaps in Copernicus user needs, and to expand the current capabilities of the Copernicus Space Component. Two of these missions are of specific relevance to ARIES and the algorithms and services developed within the project. CHIME and LSTM.

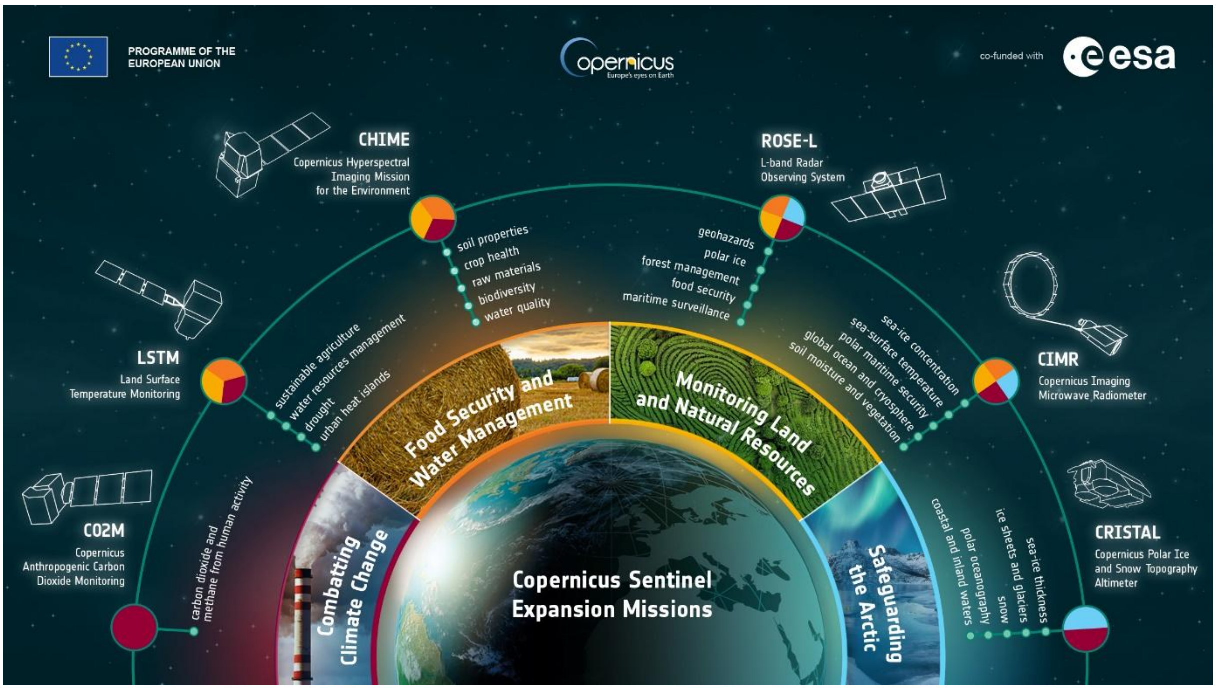

Figure 1: The Copernicus Sentinel Expansion Missions (https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Copernicus_Sentinel_Expansion_missions)

CHIME, the Copernicus Hyperspectral Imaging Mission for the Environment, is a spectrometer, which will deliver systematic high-resolution hyperspectral images to improve agricultural practices and natural resources management. Thus, for the first time, an operational hyperspectral satellite sensor of the highest quality will be available to monitor the biophysical and biochemical properties of crops.

LSTM, the Copernicus Land Surface Temperature Monitoring mission, will carry a high-resolution thermal-infrared sensor to provide observations of land-surface temperature and emissivity. The mission responds to the need to improve sustainable agricultural productivity and the management of water resources for agricultural resources as well as the prediction of droughts are a specific focus of the mission requirements.

Thus, for these Copernicus Expansion missions, the work on crop water estimation from hyperspectral PRISMA data as well as drought indicators from thermal ECOSTRESS data is potentially very valuable. In the course of the algorithm development, the potentials as well as limitations of the data sources for this specific use case have been evaluated and will be described in more detail in the next sections.

Nevertheless, it has to be kept in mind that the specifications of the currently available sensors and the future Copernicus missions are not the same, so when evaluating the potentials and limitations, these differences have to be kept in mind. The following table summarizes the most important mission specifications for all four missions.

Table 1: Mission specifications CHIME, PRISMA, LSTM and ECOSTRESS

Mission	CHIME	PRISMA	LSTM	ECOSTRESS
Swath /scene size	130km swath	30x30km	687 km swath	384 km swath
temporal resolution	12.5d	nadir revisit 29d, off-nadir targeting 7d	4 days (2 days for 2 sats)	Irregular (ISS)
spatial resolution	30m	30m	50 m (37m at nadir)	70m
Bands	400-2500nm in over 200 bands	400nm to 2505nm in 239 bands, additional PAN module (5m)	0.49, 0.665, 0.865, 0.945, 1.38, 1.61, 8.6, 8.9, 9.2, 10.9, 12 µm	1.66, 8.29, 8.78, 9.20,10.49, 12.09 µm
availability for simulation input (years)	N/A	2019 to now	N/A	2019 to now
regional availability	global	test-sites	global	global
Analysis Ready Data	BOA Reflectance	BOA Reflectance	LST, ET	LST, ET

2 Thermal Analysis – Drought Indices

2.1 Potential

Compared to land cover data (Figure 3), the high-resolution ECOSTRESS Evaporative Stress Index (ESI) index (Figure 2) can reflect the drought stress well at local scales, showing that the high-resolution missions have great potential to map agricultural drought at field level.

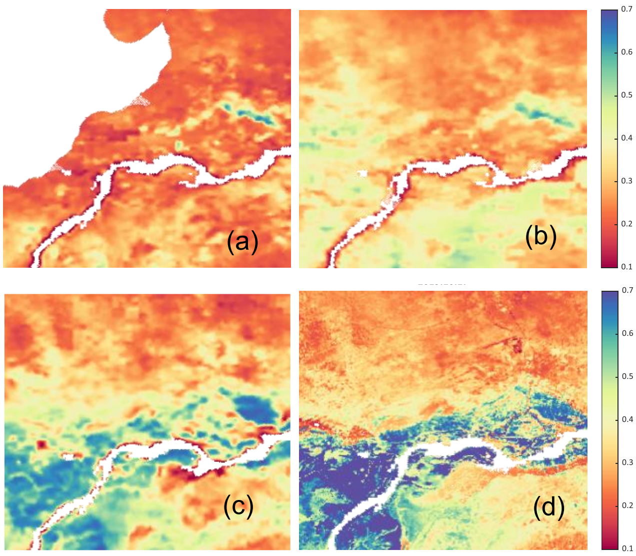

Figure 2: Monthly ESI maps at the Mali site (Lat: 16.6730 °, Long: -3.0448 °) in 2019 (a) July, (b) August, (c) September, and (d) October.

Spatial patterns of ECOSTRESS ESI align closely with land cover characteristics, notably indicating lower drought stress in wetlands during October in comparison to grassland and barren land (Figure 2). Figure 2 underscores the potential utility of ESI for localized drought stress monitoring.

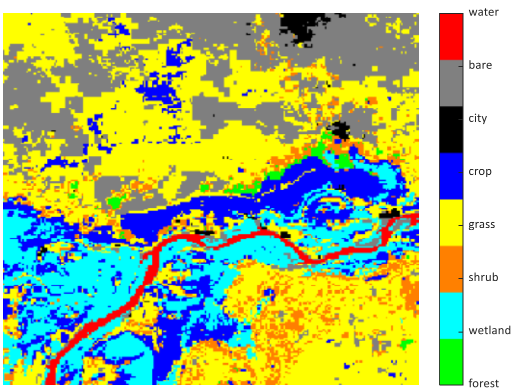

Figure 3: Land cover types surrounding the Mali site, and the spatial window size is 21 km.

The comparison presented in Figure 4, when compared with other indices, illustrates that high-resolution ECOSTRESS ESI data exhibits superior performance in delineating drought at local scales.

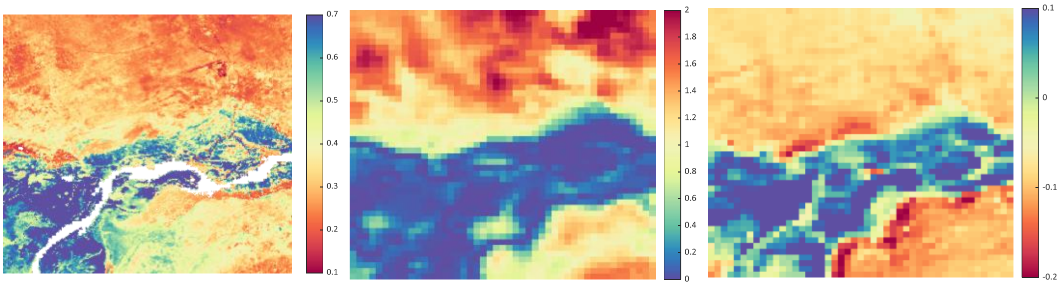

Figure 4: Local drought mapping using (a) ECOSTRESS ESI, (2) MODIS STR, and (3) MODIS NDWI

2.2 Limitations

It is noteworthy that ECOSTRESS operates with a non-fixed revisit time, rendering its ESI values incomparable across adjacent days temporally. This is attributed to the diurnal variability inherent in ESI. Furthermore, cloud cover exacerbates the limitation on data availability, resulting in highly restricted imagery at specific times of the day within a given month.

Furthermore, despite the availability of Land Surface Temperature (LST) data at fine resolution scales, other essential driving forcing data, such as surface air temperature—also crucial for Evapotranspiration (ET) calculation—still encounter limitations due to low resolutions.

2.3 Recommendations - LSTM

We strongly advocate for the LSTM mission to incorporate cloudy-sky LST recovery technologies into the official product generation process and prioritize the development of all-weather LST generation as a level-4 product for end-users. Additionally, efforts should be directed towards downscaling other crucial driving data, which also significantly influence ET estimation.

3 Thermal Analysis – High Resolution Crop Water Stress

3.1 Potential

LSTM offers a multitude of potential benefits that could significantly enhance our ability to generate a high-resolution crop water stress index. One of its primary advantages is the improved resolution compared to current EO data inputs used to compute this index (Sentinel-3 and ECOSTRESS. With LSTM, we can obtain water stress retrievals every four days for a single satellite (or two days for four satellites) with an impressive 30–50-meter resolution, around noon. This temporal resolution, coupled with the inherent high spatial resolution and high accuracy of the thermal imager, ensures a high-quality product. Additionally, directional effects are less expressed in LSTM compared to S3 due to the lower maximum viewing zenith angle of 30°, further enhancing its accuracy.

LSTM can partly replace S3 as an input for the thermal sharpening process. This would lead to more reliable land surface temperature (LST) retrieval at 20 m resolution. Compared to the S3 derived LST product at the same resolution, LSTM would provide higher LST accuracy due to a smaller sharpening ratio, offering a scaling factor of only +/- 2 instead of the substantial factor of 50. As LSTM data would not be available at daily interval, we would still need to complement the resulting time series with S3 derived LST retrieval (or SBG / TRISHNA), but overall, we believe the use of LSTM will positively impact LST accuracy at 20m resolution.

Another compelling aspect of LSTM is its ability to show directional effects with greater accuracy. Thanks to its inherent high resolution, LSTM data facilitates more precise comparisons with other sensors like ECOSTRESS, enabling a more nuanced modelling of directional effects. However, LSTM observations are limited to view zenith angles of 30°, which reduces the presence of directional effects compared to S3. Since observations are acquired around noon, directional effects in the morning and the noon can be compared. This temporal analysis could yield valuable insights into the temporal aspect of directional effects, further refining our understanding of the interaction of thermal radiation with the Earth's surface.

3.2 Limitations

Clouds still present a significant challenge for any thermal analysis as they result in the absence of data. This absence creates gaps in the LST dataset, and thus in the calculation of drought stress indicators, impacting the continuity of observations and limiting our monitoring capabilities.

In order to gain a true understanding of crop water stress, ideally this phenomenon should be tracked throughout the day. With new operational thermal missions such as LSTM, TRISHNA and SBG we will have more reliable LST measurements on a daily basis on a fixed time during the day. However, this would still need to be complemented with additional data from other sources, measuring LST during different times of the day, to gain a holistic view of crop water stress.

3.3 Recommendations - LSTM

Firstly, there is a pressing need for a reliable cloud mask. Our analysis revealed significant differences in Land Surface Temperature (LST) between ECOSTRESS and thermally sharpened S3 LST, primarily due to clouds that were not correctly identified by the S3 cloud mask. This discrepancy underscores the importance of enhancing cloud detection capabilities to ensure accurate and consistent LST estimations. Next to that, sufficient research should be devoted towards efficiently filling the observed data gaps, through combination with other data sources such as optical or radar data.

Secondly, safeguarding the accuracy of LST estimation is crucial. S3 data has shown a tendency to overestimate LST, attributed to inaccuracies in assigning land cover types and their corresponding split-window coefficients within the LST retrieval algorithm. Addressing these issues is paramount to rectify biases and enhance the overall reliability of LST data derived from LSTM.

Thirdly, implementing a directional correction on the LSTM-derived LST measurements is highly recommended. This correction would not only improve the quality of the LST product by itself, but also enhance comparability with other sensors such as SBG and TRISHNA, hence resulting in a more reliable and consistent daily time series of LST at global scale. A generic directional correction approach, involving one parameter per tile, could already yield notable improvements. However, for enhanced data consistency, a more refined pixel- or field-specific correction method would be even more beneficial. These enhancements would significantly contribute to the overall effectiveness and accuracy of LSTM in analyzing and generating crop water stress index data.

4 Hyperspectral Analysis

4.1 Potential

- **Hyperspectral Analysis of Absorption Features like e.g. plant H2O-absorptions:** The ability to use the absorption features of vegetation is one of the main advantages of hyperspectral analysis over multispectral analysis. Since individual absorptions can be assigned to specific plant properties like e.g. the water content of the plant, it is possible to devise new and targeted indices for the derivation of these parameters, which are less dependent on other plant variables than their multi-spectral counterparts, which have to use broader wavelength ranges. This makes the accuracy of hyperspectral indices higher than that of multispectral, broad-band ones.

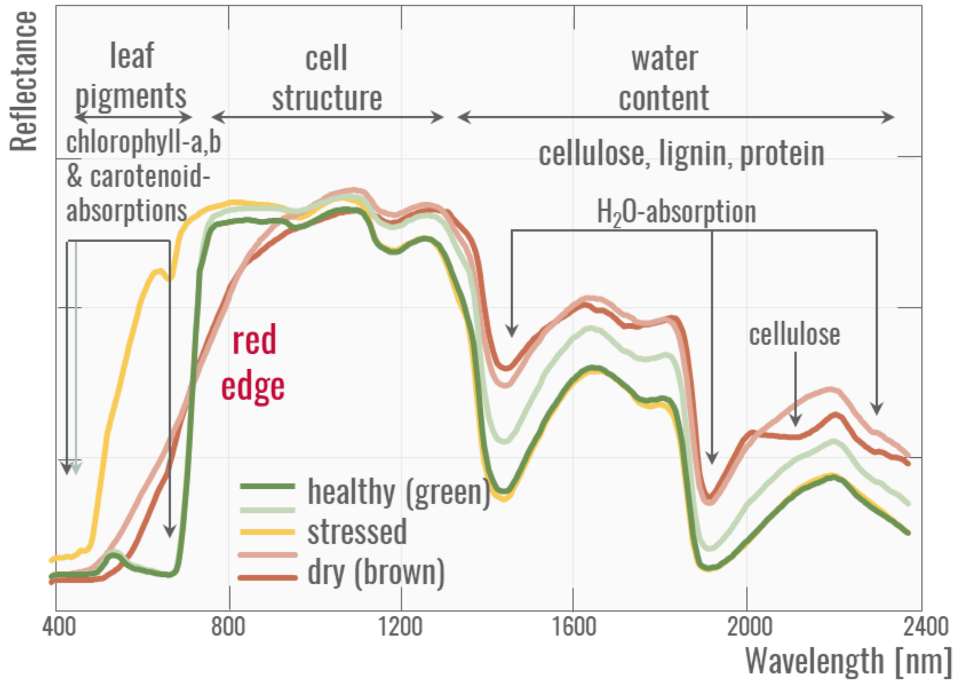

Figure 5: Absorption features of vegetation (Berger et al. 2020)

- **Retrieval of Variables via Inversion of Radiative Transfer Modelling:** Radiative transfer modelling allows to derived quantitative values of biophysical, chemical and structural plant parameters. However, it is well-known, that the inversion of radiative transfer models is an ill-posed problem. Using hyperspectral data, the ill-posed problem does not disappear, but the much higher number of bands adds an additional dimensionality that allows for the simultaneous retrieval of several plant variables. Additionally, the individual absorption features visible in the hyperspectral data make it possible to differentiate between the different biochemical and physical plant parameters much better than via their broad-band multi-spectral features. This allows a higher accuracy of the parameter retrieval.

4.2 Limitations

- **Increased Data Volume of Hyperspectral Data:** The data volume of the hyperspectral data is necessarily high, as it has 10-20 times the number of bands as multi-spectral data. This is a limitation especially when using an inversion of a radiative transfer model as analysis method. In a look up table approach for example, all bands have to be added to the look up table, increasing its size also by 10-20 times. This means that radiative transfer models in tool boxes (even in the EnMAP Toolbox) often reach their limits, due to either memory issues or large computation times. Hence, new methods of retrieval e.g. via AI methods have to be devised and implemented to actually make use of the full information content of the hyperspectral data.

- **Temporal Resolution:** In agricultural applications, the temporal resolution of the data is very important, as the phenological development of the crops proceeds quite fast. Dense time-series are necessary to capture the plant development, both in terms of biomass growth as well as in terms of water demand. Hence, the temporal resolution of CHIME with 12.5 days nominal revisit is deemed to be a limitation. Average cloud cover in areas which are useful for cropping is above 50%, so this means that on average one scene per month is all that can be expected from CHIME. In turn, this means that for applications were management decisions have to be made fast, like e.g. for irrigation advice, the temporal resolution of CHIME is not enough. The following figure shows an analysis of the average number of expected acquisitions, assuming an overflight every 12 days (orbit overlays not included) and using weather conditions of 2022 and 2023 from ERA5 reanalysis data for 12pm UTC as input. Assuming that any image with less than 55% of cloud cover can be used in agricultural analysis, this leads to a maximum of 24 acquisitions in Saharan Africa (where there is however no agriculture) and a minimum of less than 6 acquisitions per year in tropical regions.

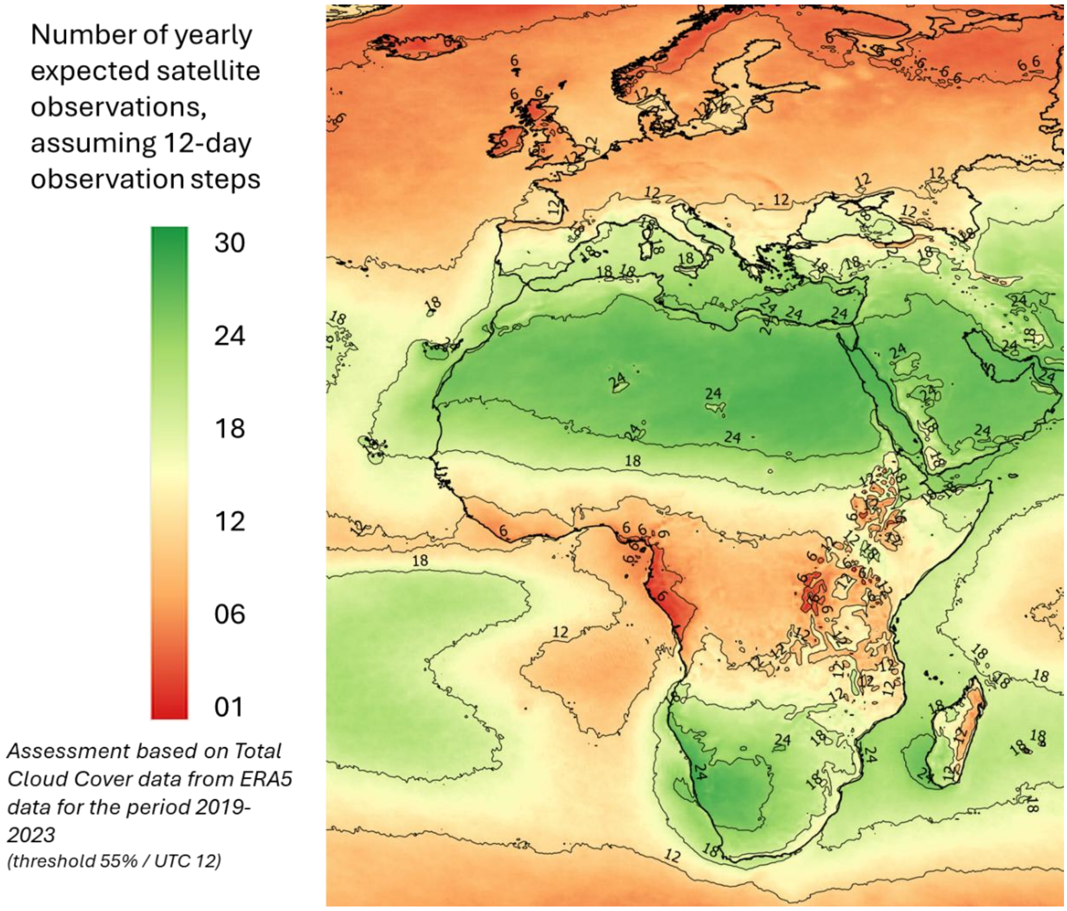

Figure 6: Number of yearly expected satellite observations assuming 12-day observation steps

- **Spatial Resolution of 30m:** All agricultural applications have to capture individual agricultural fields. To allow for any application, each field needs to be covered by at least 1 to 50 pure pixels, where 50 pixels allows smart farming operations. The figure below shows the average field sizes in different European regions. At a resolution of 20m, 80-90% of all farms can be covered, at a resolution of 30m already 25-45% of all fields are lost depending on the region and its average field sizes.

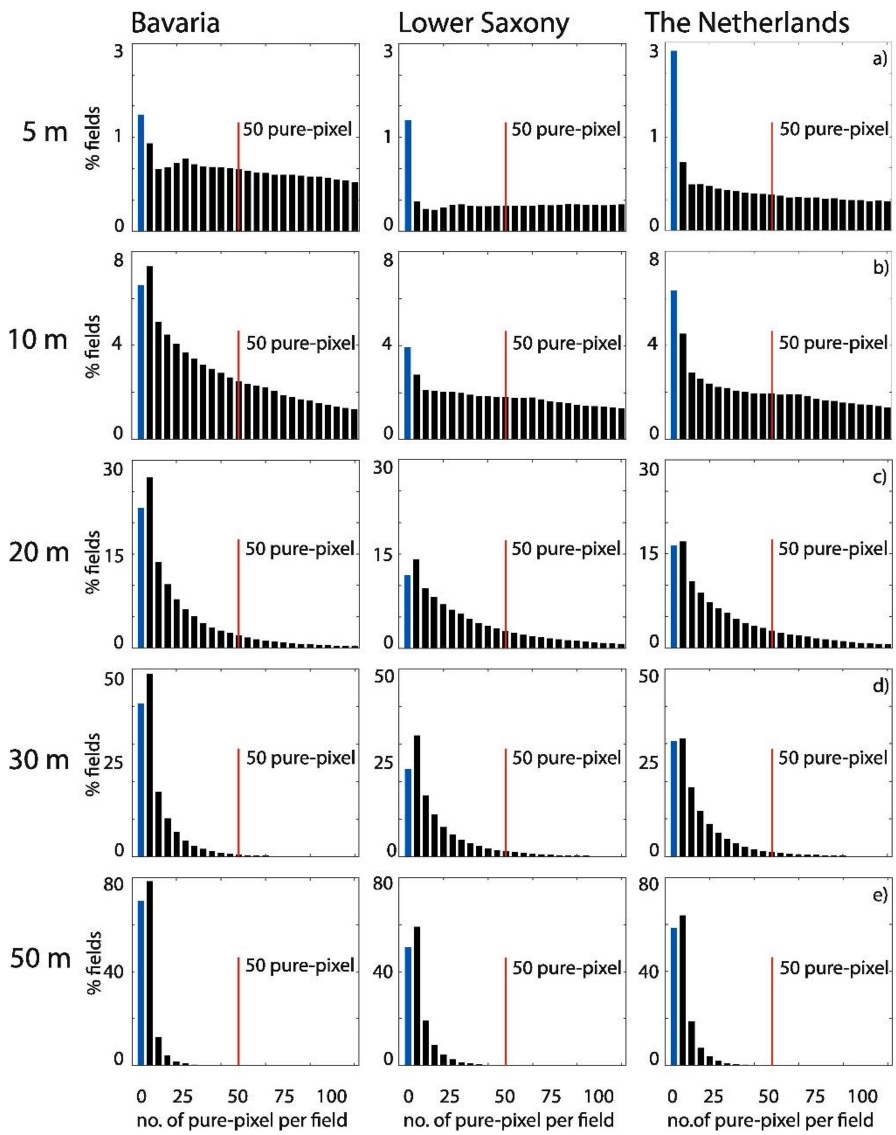

Figure 7: ***Amount of pure pixel at different spatial resolutions for average field sizes in different regions (Meier et al. 2020)***

The second figure (below) shows the percentage of lost fields with changing resolution in Bavaria. A change from 20 to 30m means that more than twice as many fields can no longer be represented by pure pixels, especially in the case of cereals. While these numbers are calculated for European conditions, average field sizes in Africa vary even more widely. Subsistence farming, which makes up a large part of fields, usually has very small field sizes, while commercial farms with pivot irrigation tend to have much bigger fields.

Nevertheless, the European numbers give an impression of the limitations of the 30m spatial resolution.

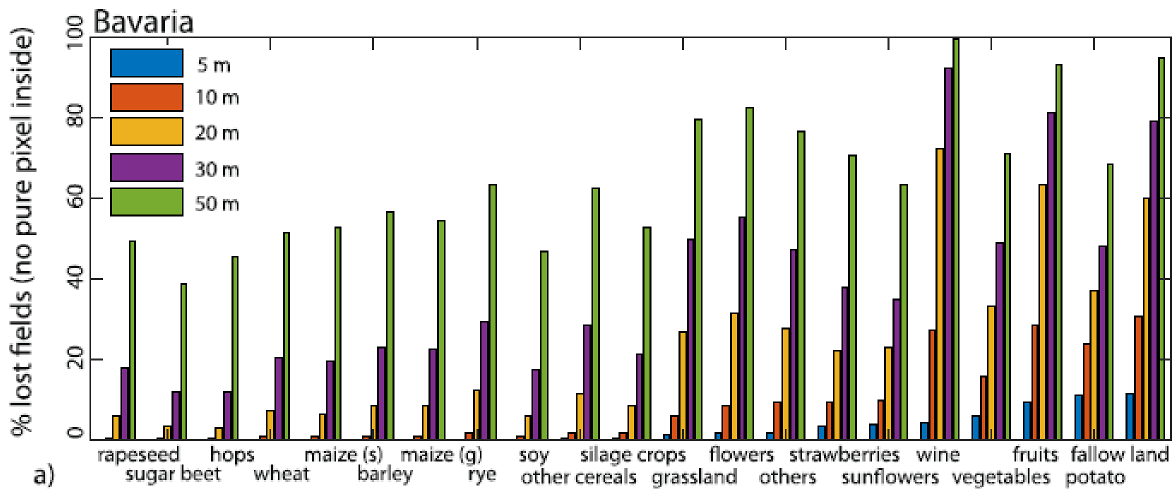

Figure 8: Percentage of 'lost fields' of different crop types in Bavaria for the selected rasterization resolutions of 5, 10, 20, 30 and 50 m. Maize (s) = silage maize, maize (g) = maize grain, silage crops = silage crops without maize. (Meier et al. 2020)

4.3 Recommendations – CHIME

- **High spectral quality is of essence for absorption band analysis:** Using small band ratios for absorption analysis means that noise in the images can easily make it impossible to derive accurate quantitative results. Below is an example using EnMAP data and the EnMAP Toolbox to derive plant water content. There is a systematic striping noticeable in the results, which cannot be explained other than with systematic sensor calibration issues. Issues like these will make the accurate retrieval of plant parameters much harder and will hinder user uptake of CHIME.

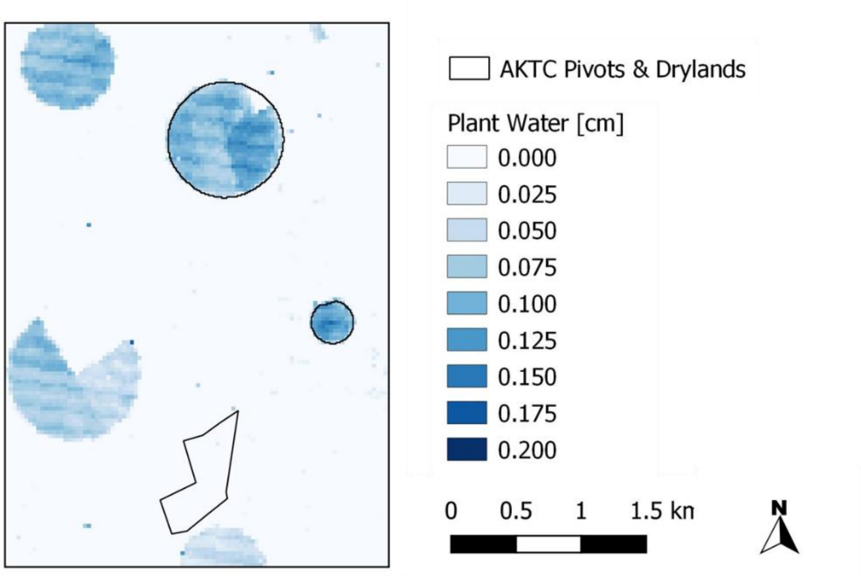

Figure 9: Example of striping in EnMAP data after plant water retrieval with EnMAP toolbox

- **High quality pre-processing:** To fully utilize the information depth of the data, high quality pre-processing is necessary. This obviously includes the spectral domain, but also the spatial domain. A geometric correction that aligns CHIME with Sentinel-2 will make a synergistic use of the two data sources much easier, especially if a (semi-) automated way of time series analysis is the goal. With the current hyperspectral sensors PRISMA and EnMAP, every scene has to be checked and its location corrected if necessary. This is an extra step, that costs a lot of time and makes the use of available tools that use the field boundaries to mask the image and only produce results for the relevant fields impossible for users who don't have the necessary knowledge on how to geometrically correct the images.

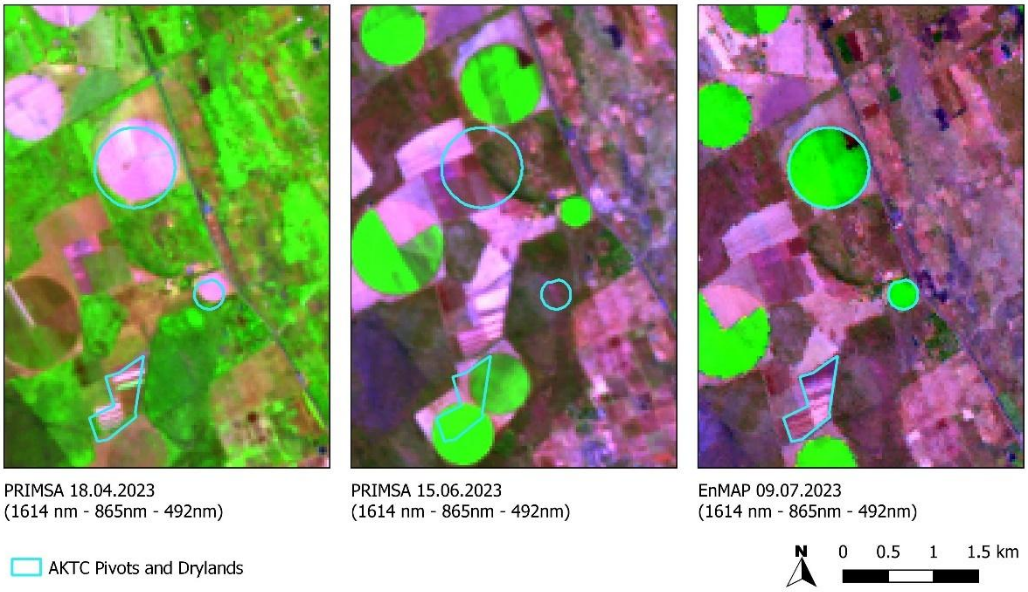

Figure 10: Geometric offsets observed in PRISMA and EnMAP data at the AKTC test site.

- **Tools that can handle the data volume:** Efficient tools that can handle the high dimensionality and large volume of the hyperspectral data without crashing or needing so much time for computation that the delay in agricultural product delivery becomes too long are necessary. Additionally, these tools should be able to process significant areas without loss of efficiency or accuracy, so that the full benefits of the hyperspectral data can be utilized. Parallelized software and cloud computing can support these goals.

5 Conclusion

In conclusion, the PRISMA and ECOSTRESS datasets are valuable data sources to use in preparation for CHIME and LSTM. Possible bottlenecks are already becoming apparent in the use of these datasets and can be taken into account in the implementation of CHIME and LSTM processing. But maybe even more importantly, the additional benefit of these new missions can be showcased and algorithms and processors that can later be adapted to the new data sources can already be prepared. This way, the user community will have pre-made, easy-to-use tools available that are targeted to their needs, so that they can start using CHIME and LSTM data as soon as they become available.

6 References

Berger, K., Verrelst, J., Atzberger, C., Weiss, M., Steinhauser, S., Wocher, M., Foerster, S. & Kuester, T. (2020). Retrieval approaches of vegetation traits from imaging spectroscopy data – Overview of methods for the quantification of bio-geophysical and biochemical vegetation traits. HYPERedu, EnMAP education initiative, LMU Munich; originally published September 2020, revised February 2023.

Meier, J., Mauser, W., Hank, T. & Bach, H. (2020). Assessments on the impact of high-resolution-sensor pixel sizes for common agricultural policy and smart farming services. European regions, Computers and Electronics in Agriculture, Volume 169, https://doi.org/10.1016/j.compag.2019.105205