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USING UAV-DERIVED PLANT HEIGHT AS AN ESTIMATOR FOR BIOMASS AND N-UPTAKE

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ABSTRACT:

In Precision Agriculture applications, the knowledge of the N-uptake of crops in a spatial context is a precondition for precise N-fertilization. Therefore, non-destructive methods to determine N concentration or N-uptake of crops are of key interest. In this contribution, we will present an approach based on UAV-based crop height analysis to estimate N-uptake. The hypothesis is that biomass can be very well estimated using UAV-derived crop height. It is also known that biomass is highly correlated with N-uptake. Hence, we propose to use UAV-derived crop height as a direct estimator for N-uptake. We will present results from a winter wheat field trial comprising six varieties, three different N amounts, and five repetitions. Multitemporal models have been created from data of the growing season 2020 with a promising performance for biomass ($R^2 = 0.91$) and N-uptake ($R^2 = 0.72$). The two linear regression models have been applied to a similar independent data set from the following year, 2021. The results are promising for biomass ($R^2 = 0.82$) and N-uptake ($R^2 = 0.75$). Based on our findings, we conclude that UAV-derived crop height - as a structural crop trait - can robustly serve as an estimator for biomass and N-uptake in winter wheat.

1. INTRODUCTION

Nitrogen fertilization is of key importance in crop production. However, overuse of N fertilizers is related to severe environmental pollution like eutrophication of surface and groundwater bodies, as well as the emission of nitrous oxide. These environmental threats are directly connected to precision agriculture (PreAg) which aims to apply the right amount of nutrients, e.g. N, at the right time and location (Mulla 2013). The key idea is to optimize inputs while maximizing yield and reducing environmental costs. For N fertilization, optimization is equivalent to reducing the amount of N due to overuse.

For decades, spectral approaches using proximal or remote sensing have been investigated to develop methods to estimate crop biomass, nitrogen concentration, and N-uptake (Bareth 2021). Many of these studies utilize vegetation indices (VIs) to estimate crop traits (Li et al. 2010, Li et al. 2008). For nitrogen, Berger et al. (2020) state that in most studies the relation of chlorophyll to N was used and the N content in crop proteins was neglected. The latter resulted in poor Pearson correlation coefficients. However, Aasen and Bareth (2019) outline the potential of structural estimators to derive biomass. This was investigated by Bendig et al. (2015) and Tilly et al. (2015). In both studies, it could be proven that crop height serves as a robust estimator for biomass. Besides, it is well known that biomass negatively correlates to N concentration with increasing biomass during crop growth. Tilly and Bareth (2019) investigated the correlation of biomass, estimated from crop height, and destructively sampled N concentration and documented a high R^2 of < 0.85, while the analysis of spectral data yielded a lower R^2 of < 0.70.

Therefore, the objective of this study is on the UAV-derived crop height as an estimator for biomass and N-uptake for winter wheat. We will focus (i) on the UAV-based image acquisition, (ii) on the Structure from Motion and Multiview Stereopsis (SfM/MVS) analysis workflow, and (iii) on a first linear regression analysis of UAV-derived crop height versus biomass and N-uptake.

2. STUDY AREA AND METHODS

2.1 Study Area

The winter wheat experiment field is located at the University Experimental Farm of Bonn University, the Campus Klein-Altendorf, which is located near Bonn in Western Germany (Fig.1).

Figure 1. Location of the winter wheat field experiment (Jenal et al., 2021).

The winter wheat field experiment is a randomized block design with five repetitions (Fig.1). Each repetition consists of six different winter wheat varieties organized in three nitrogen treatments (0, 120, 240 kg/ha). The individual plots are 7 x 1.5 m large. One repetition is used for destructive sampling during the growth period. For each UAV campaign, 1 x 0.3 m large sampling areas are destructively harvested for biomass and N analysis (see Fig.1).

2.2 UAV-based Image Acquisition

For the UAV-based data acquisition, a DIJ P4RTK was used. The P4RTK is equipped with an integrated, fully gimbaled 1” 20 MP RGB sensor (Fig.2). Additionally, the P4RTK was linked to a base station. Ground control points (GCPs) were installed in the field experiment. An orthogonal flight pattern having 80% image overlap was flown 25 m above ground. Images were taken in NADIR geometry.

Figure 2. UAV image acquisition with a DJI P4 RTK with base station and GCPs.

2.3 SfM/MVS Analysis Workflow

To derive UAV-based crop height, a Structure from Motion and Multiview Stereopsis (SfM/MVS) analysis workflow utilizing Agisoft Metashape and Esri ArcGIS was applied. For each campaign, almost 400 overlapping images were acquired. In Fig.3, the image overlap of more than 90% is visualized. The low flying altitude of 25 m resulted in a ground sampling distance (GSD) of 0.66 cm for the Digital Orthophoto (DOP). The RMSEs for X, Y, and Z are 0.6, 0.59, and 0.55 cm, respectively. The overall RMSE is 1.0 cm. From the generated point cloud, a Digital Surface Model (DSM) was computed in Metashape with a resolution of 1.32 cm, which is double compared to the DOP. DSMs were computed for 8 April, 28 April, 13 May, 26 May, 12 June, and 1 July 2020. To derive crop height for each UAV campaign, the Digital Terrain Model (DTM) was subtracted in ArcGIS from the DSMs. The DTM, for which UAV data acquisition was carried out on 17 February 2020, was created using the same SfM/MVS analysis workflow. The SfM/MVS analysis workflow to compute UAV-derived crop height was introduced and described by Bendig et al. (2013) for the first time (Fig.5).

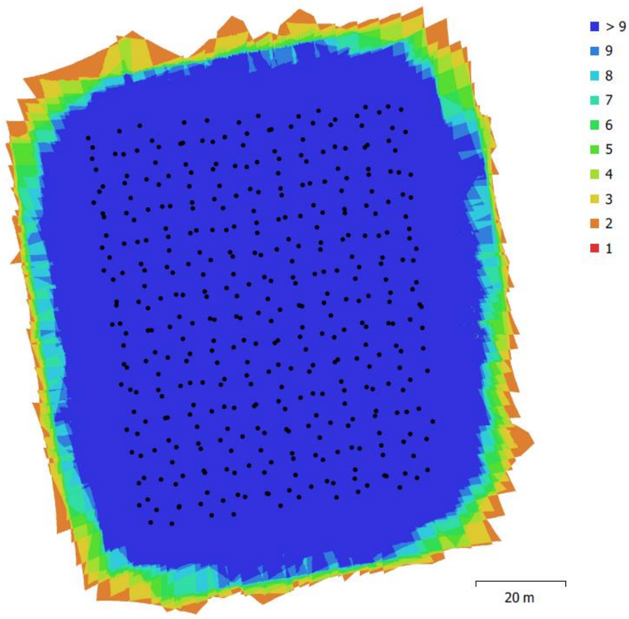

Figure 3. Image overlap of SfM/MVS analysis.

In Fig.4, the DOP, crop height, and location of the GCPs are shown for an additional campaign on 2 June 2020. In the DOP, the N treatments and location of the destructive sampling are visible. In the enlarged visualization of Fig.4, the individual sowing rows are recognizable due to the very high spatial resolution of the UAV-based image data acquisition.

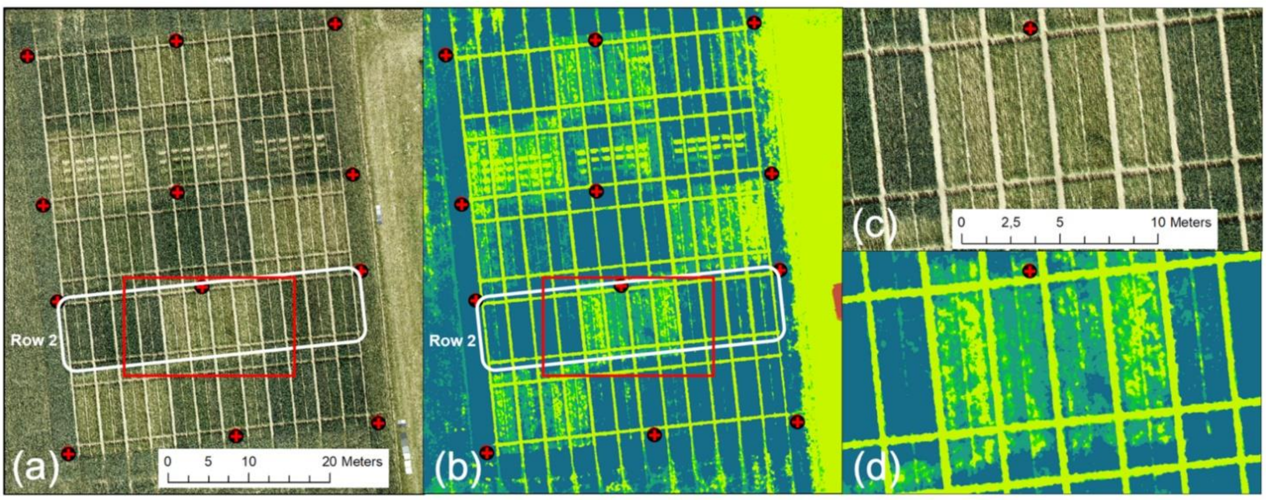

Figure 4. Results of the SfM/MVS analysis workflow: (a) and (c) DOP, (b) and (d) crop height (Jenal et al. 2021).

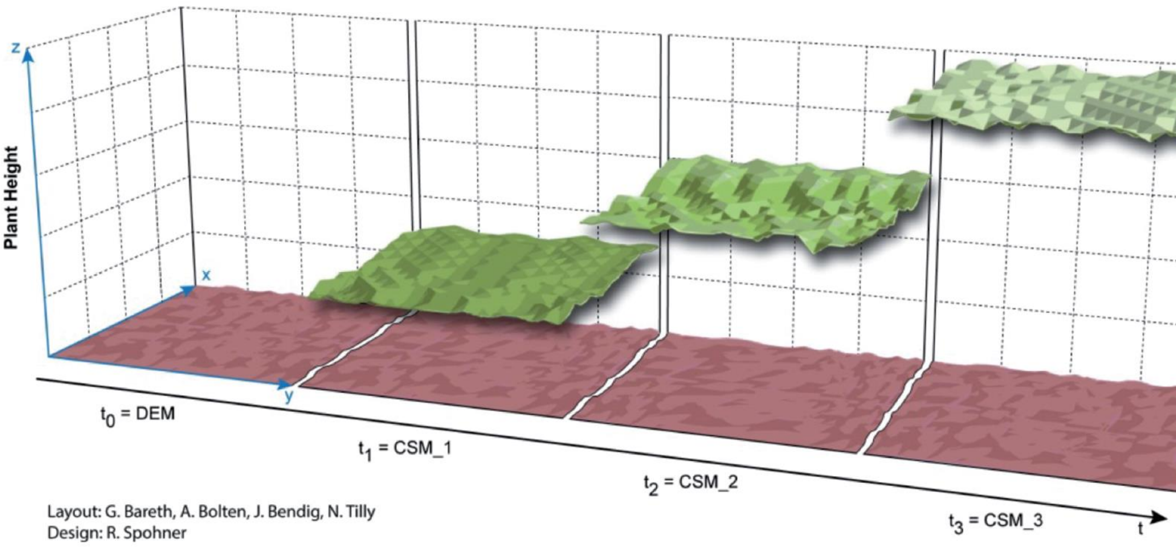

Figure 5. Multi-temporal Crop Surface Models (CSMs) to derive crop height and crop growth (Bendig et al. 2013).

In Fig.5, the method of deriving UAV-based crop height is visualized described by Bendig et al. (2013). In a first step, a Digital Elveation Model (DEM) after sowing and of bare soil surface is generated representing the surface before crop emergence (t_0). Afterwards, UAV campaigns are carried out in distinct growing stages (t_1 to t_n) for generating Digital Surface Models of the crop surface, the Crop Surface Models (CSMs). Using GIS raster analysis tools for subtracting the CSMs for t_1 to t_n by the DEM of t_0, crop height can be computed for each CSM date.

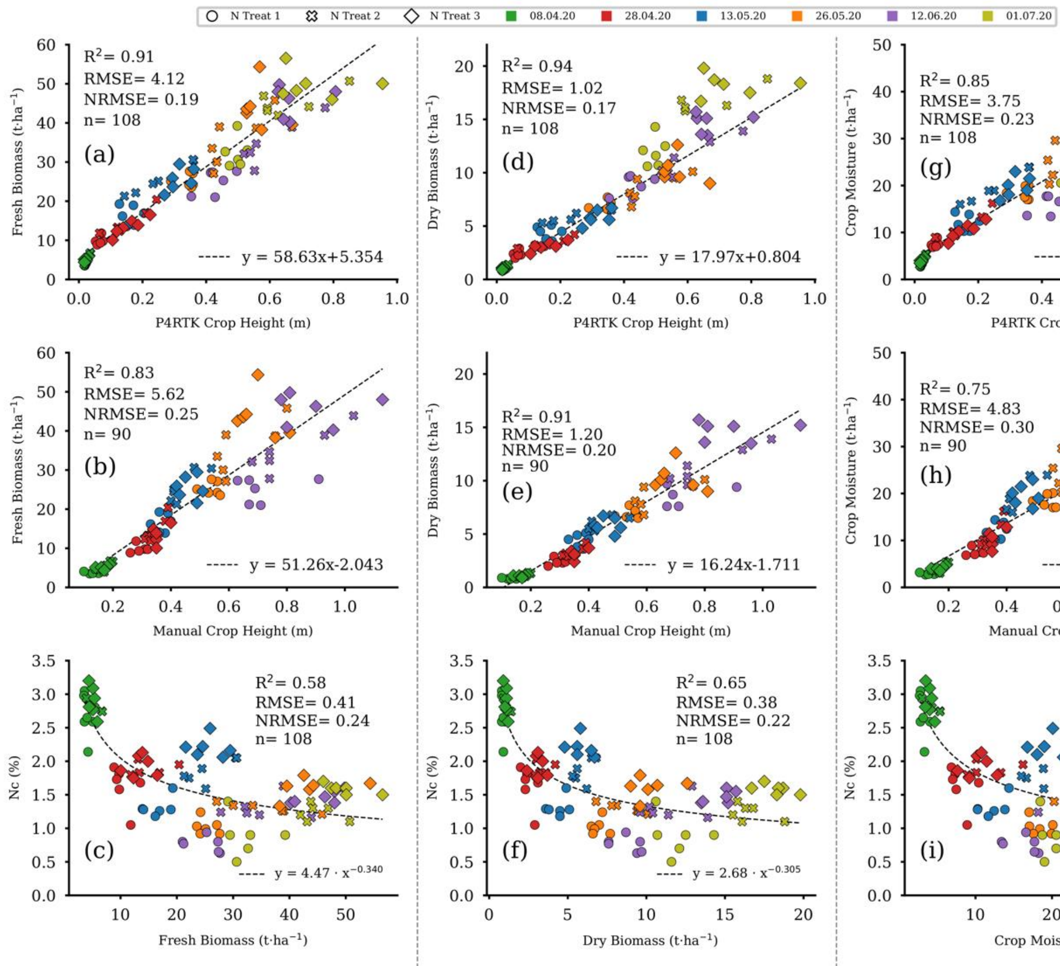

Figure 6. Plotting manual and UAV-derived crop height against fresh and dry biomass, as well as crop moisture. N concentration (Nc) against fresh and dry biomass, as well as crop moisture (Jenal et al. 2021).

3. RESULTS

The crop height analysis based on the image data acquired with the P4RTK against biomass is shown in Fig.6 and is published by Jenal et al. (2021). Besides, in Fig.6, manually measured crop height is plotted against biomass and N concentration. As expected, the UAV-derived crop height performs very well, resulting in R^2 of 0.91, 0.94, and 0.85 for fresh biomass, dry biomass, and crop moisture, respectively. The UAV-derived crop height performs better than the manual measurements having R^2 of 0.83, 0.91, and 0.75 for fresh biomass, dry biomass, and crop moisture, respectively. Finally, biomass is negatively correlated with N concentration showing moderate R^2 of 0.58, 0.65, and 0,54 for fresh biomass, dry biomass, and crop moisture, respectively.

The excellent performance of the UAV-derived crop height with dry biomass for the growth period of 2020 (see Fig.6-d; R^2 of 0.94) was used to apply the regression model in a first step to one growing date of the crop growth period of 2021. For 12 May 2021, a similar UAV-derived crop height data set was created and used in the linear regression model from 2020 to estimate dry biomass, and to evaluate the model results against destructive field samplings. For the latter, the destructive sampling was doubled per date in 2021 (n = 0.36). The results are shown in Fig.7 and are very promising, having a R^2 of 0.82 and a RMSE of 1,15 t/ha. Especially because the weather conditions in 2021 were very different from those in 2020.

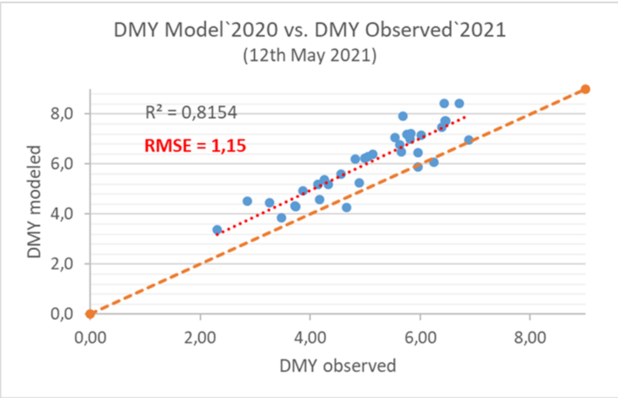

Figure 7. Evaluation of a dry biomass model for winter wheat using UAV-derived crop height only.

The primary objective of this study is the estimation of N-uptake using UAV-derived crop height. For that purpose, the UAV-derived crop height is plotted against N-uptake for the growth period 2020 (Fig.8). The performance is good, having an R^2 of 0.72. The weaker performance compared to the R^2 for biomass can be explained by the moderate R^2 of N concentration versus biomass (see Fig.6-f). For the calculation of N-uptake, both, biomass and N concentration are used. So, the weaker relation of N-concentration versus crop height is contained in the N-uptake values. However, the analysis is more promising than spectral approaches using narrow band Vis which only perform poor to moderate (Li et al. 2008; Li et al. 2010).

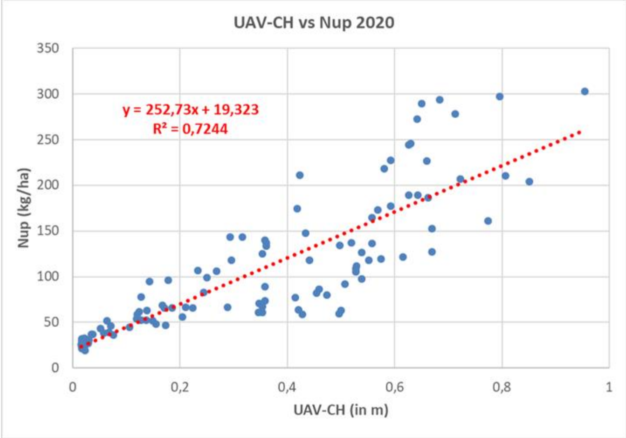

Figure 8. Plotting UAV-derived crop height against N-uptake.

The established regression model for N-uptake (Fig.8) was applied in a first step to one growing date of the crop growth period 2021. For 12 May 2021, a similar UAV-derived crop height was used in the linear regression model to estimate N-uptake and evaluate the model results against destructive field samplings. Again, the destructive sampling was doubled per date in 2021 (n = 0.36). The results are shown in Fig.8 and are very promising, having an R^2 of 0.75 and a RMSE of 34 kg/ha. Especially because the weather conditions in 2021 were very different from those in 2020.

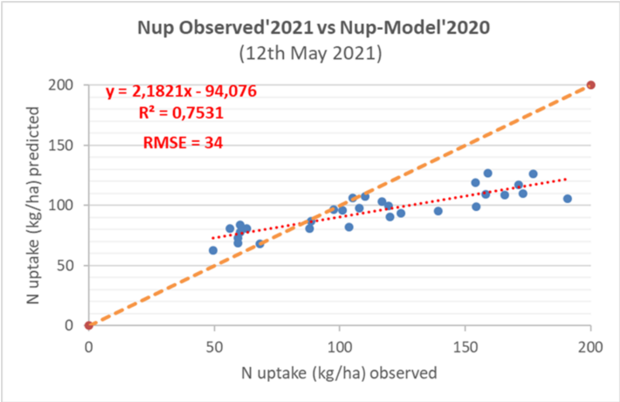

Figure 9. Evaluation of a dry biomass model for winter wheat using UAV-derived crop height only.

4. DISCUSSION & CONCLUSION

The overall objective of this study was to evaluate for the first time if UAV-derived crop height can be used as an estimator for N-uptake in crops, in our study on winter wheat. Multiple UAV campaigns were carried out in 2020 and for each date crop height was computed using a SfM/MVS analysis workflow. From the 2020 data, two regression models for dry biomass and N-uptake were established and applied on one date in the growth period of 2021. The first evaluation of the modelling results is very promising, showing a high R^2 of 0.82 and 0.75 for dry biomass and N-uptake, respectively. However, this is a first study establishing the regression model only on one growing season and applied the model only on one date in 2021. Hence, further analysis and evaluation is needed. We acquired data for this winter wheat field experiment for four years (2020-2023), including the destructive sampling of biomass and N. We will evaluate regression models specific for winter wheat varieties and multiple growing seasons.

The results correspond very well with published studies. Numerous publications prove the very good performance of UAV-derived crop height in estimating biomass (Bendig et al. 2014; Viljanen et al. 2018). The application of using UAV-derived crop height to estimate N-uptake is not yet well established. But the results clearly outperform spectral approaches (Li et al. 2008; Li et al. 2013) and are in line with the findings of Tilly and Bareth (2019) using crop height to estimate N.

Promising approaches for deriving crop height with UAVs are also UAV-borne LiDARs. Ten Harkel et al. (2020) applied an UAV-LiDAR approach for biomass estimation for sugar beet and winter wheat with promising results (R^2 of 0.68 and 0.82, respectively) and for potatoes with moderate performance (R^2 of 0.24). Hütt et al. (2023) confirmed for winter wheat the promising potential of UAV-LiDARs stating a R^2 of up to 0.78 for biomass and of 0.87 for N uptake. In the latter study, the authors applied UAV LiDAR metrics which were developed for forestry applications (Drake et al. 2002; Stefanidou et al. 2020). Those results clearly demonstrate the potential of UAV-derived structural crop properties to estimated crop traits. For a final evaluation of the presented approach, more multi-annual data sets are needed with model validation between independent data sets.

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