Results from field trials with spring crops 2023

Halm til det hele (Straw for all)
Work package 1

The field trials

Two field trials were established in spring barley and spring wheat, each with five varieties in two different plant densities. For barley, the two densities were 200 and 300 plants/m^2. For wheat, the two densities were 300 and 450 plants/m^2. Each trial was laid out in a randomized complete block design, with four blocks. The seedbeds were prepared 26th of April and sowing took place 27th of April. Germination was decent for both crops. Both crops were harvested 22nd of August. Weather conditions for the growth season are shown in Figure 1. The timing of the major growth stages is reported in Table 1.

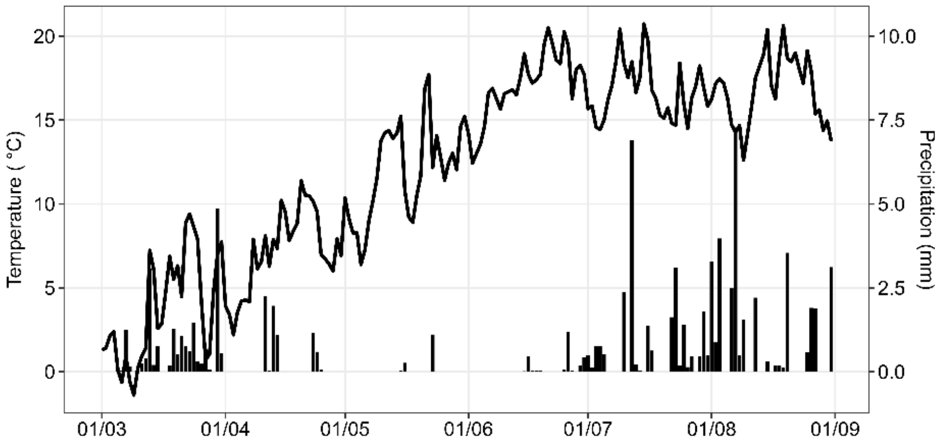

Figure 1: Temperature and precipitation in Taastrup for the growth season 2023 for spring barley and spring wheat.

Table 1: Approximate timing of the major growth stages in 2023.

Date	BBCH growth stage
2023-05-10	11
2023-05-17	12-13
2023-05-24	21
2023-06-07	31-32
2023-06-22	57-59
2023-06-30	65
2023-07-07	69
2023-07-11	71
2023-07-13	71-73
2023-07-19	81-82
2023-07-27	85-87
2023-08-14	90

Statistical analysis

Yield and yield components were analyzed using a linear mixed model with variety, density, and their interaction as fixed effects, and block as random effects. All reported correlations were Pearson correlations. Grain and straw yield refers to dry weight.

Prediction models were based on linear regression models. Different sets of predictor variables were included in different models. The included variables were digital height, RGB- and multispectral vegetation indices at the timing with the best correlation to the straw yield, area under vegetation index (AUVIC) for different RGB and multispectral vegetation indices, and grain yield (for adjustment). Only models with a maximum of 4 predictor variables were included due to the limited size of the data set. Validation of the prediction models was based on 4- and 5-fold cross-validation. In the 4-fold cross-validation, the model was fitted to data from three blocks and evaluated in the last block. This was repeated four times, each time leaving out a new block, and the mean correlation between predicted and observed straw yield in the block left out (the test set) was reported. In the 5-fold cross-validation, the model was fitted to data from four varieties and evaluated in the remaining variety. This was repeated five times, each time leaving out a new variety and the mean correlation between predicted and observed straw yield for the variety left out was reported. The final model was obtained as a weighted average of the model trained on the different subsets of the data with weights according to the performance in the corresponding test sets.

All analyses were made in R version 4.2.0. The extension package lme4 was used for fitting linear mixed models.

Yield

Estimated grain and straw yield by variety and density are presented in Figures 2 and 3 for barley and wheat, respectively. In barley, the grain yield varied from 3.50 t/ha (95%-CI: 3.04 - 3.96 t/ha) in low-density Halfdan to 4.67 t/ha (95%-CI: 4.21 - 5.13 t/ha) in high-density Wish, while the straw yield varied from 2.00 t/ha (95%-CI: 1.60 - 2.40 t/ha) in low-density Flair to 2.81 (95%-CI: 2.41 - 3.21 t/ha) in low-density Wish. Wish and Skyway had a significantly higher grain yield in the low plant density compared to Flair and Halfdan. In the high plant density, Wish showed a tendency for a higher grain yield compared to all of the remaining varieties, though the difference was not significant. In the low plant density, wish had a significantly higher straw yield compared to Flair, while in the high density, Halfdan and Skyway had a significantly higher straw yield compared to Wish.

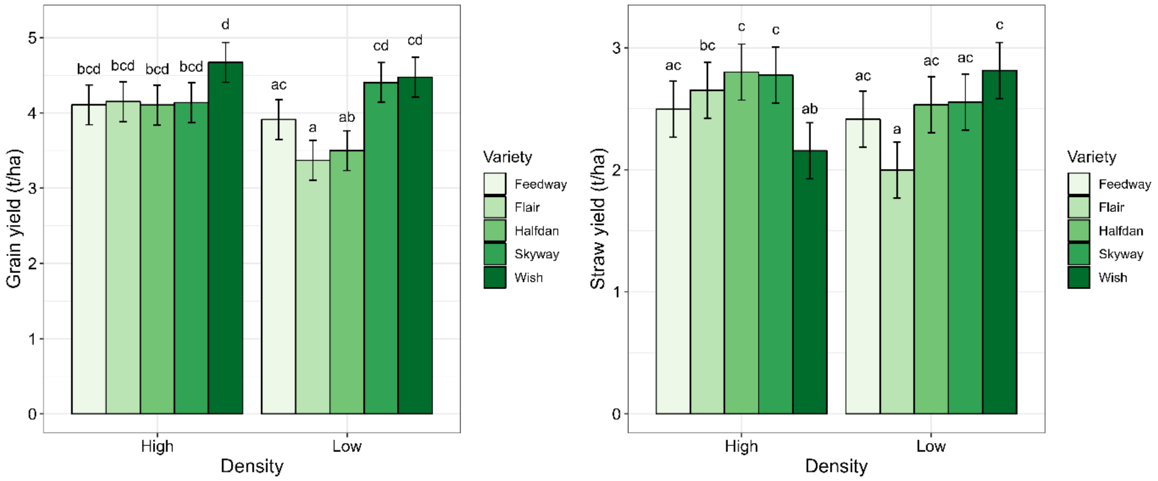

Figure 2: Grain and straw yield for spring barley by variety and plant density. Error bars represent standard errors. Treatments that do not share any letters were significantly different.

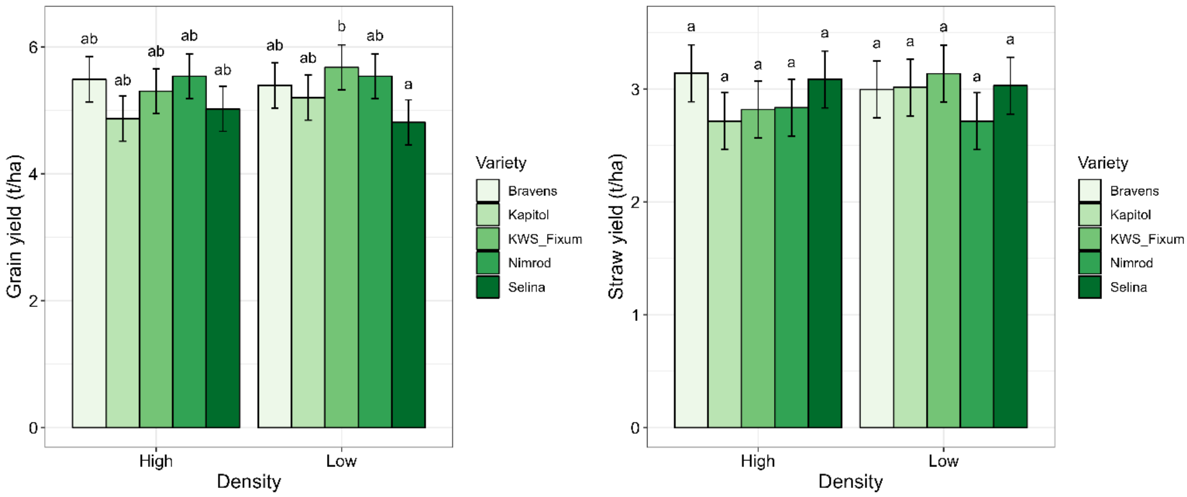

Figure 3: Grain and straw yield for spring wheat by variety and plant density. Error bars represent standard errors. Treatments that do not share any letters were significantly different.

In wheat, the grain yield varied from 4.81 t/ha (95%-CI: 4.18 - 5.45 t/ha) in low-density Selina to 5.68 (95%-CI: 5.04 - 6.32 t/ha) in low-density KWS_Fixum, while the straw yield varied from 2.72 t/ha (95%-CI: 2.27 - 3.16 t/ha) in low-density Nimrod to 3.14 t/ha (95%-CI: 2.70 - 3.59 t/ha) in high-density Bravens. KWS_Fixum had a significantly higher grain yield compared to Selina in the low density, while no other differences in grain yield were found. The straw yield was similar for all wheat varieties and across densities. The straw fractions differed between the wheat varieties (Table 2).

Table 2: Straw fractions in wheat. Fractions are based on the separation of straw fractions in one plot for each of four wheat varieties.

Variety	Straw and leaves	Rest
Nimrod	49.1%	50.9%
Kapitol	52.3%	47.7%
Selina	42.5%	57.5%
Bravens	54.7%	45.3%

Plant counting

Manual plant counting in the field was done by placing a 1 m stick along a row of plants at four different locations in each plot and then counting the plants/m. Numbers were converted to plants/m^2 by taking into account the row distance.

Digital plant counting was based on images taken by the field robot. A deep learning model was trained. More details on the digital plant counting can be found in the note: “Plant Counts Using Computer Vision And Deep Learning”. Correlations between digital and manual counts are shown in Figure 4.

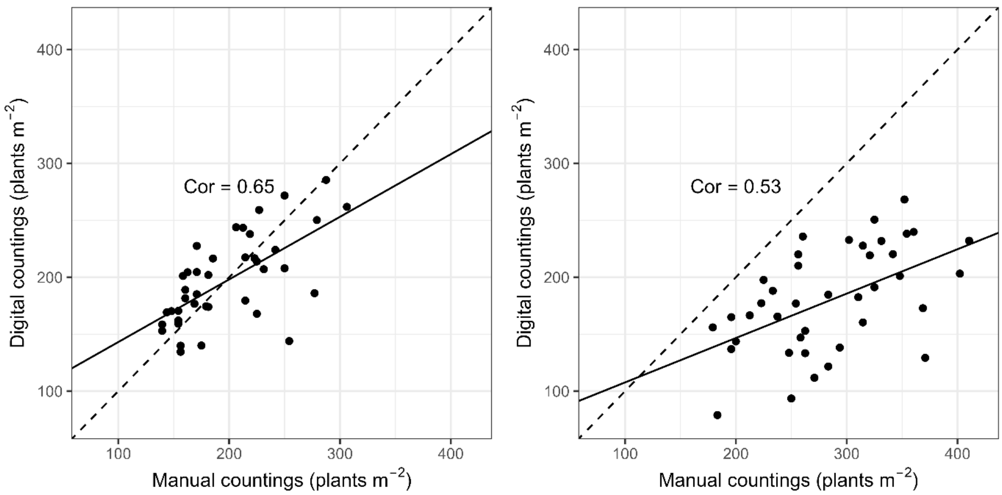

Figure 4: Correlations between digital and manual plant counts. Left: Barley. Right: Wheat.

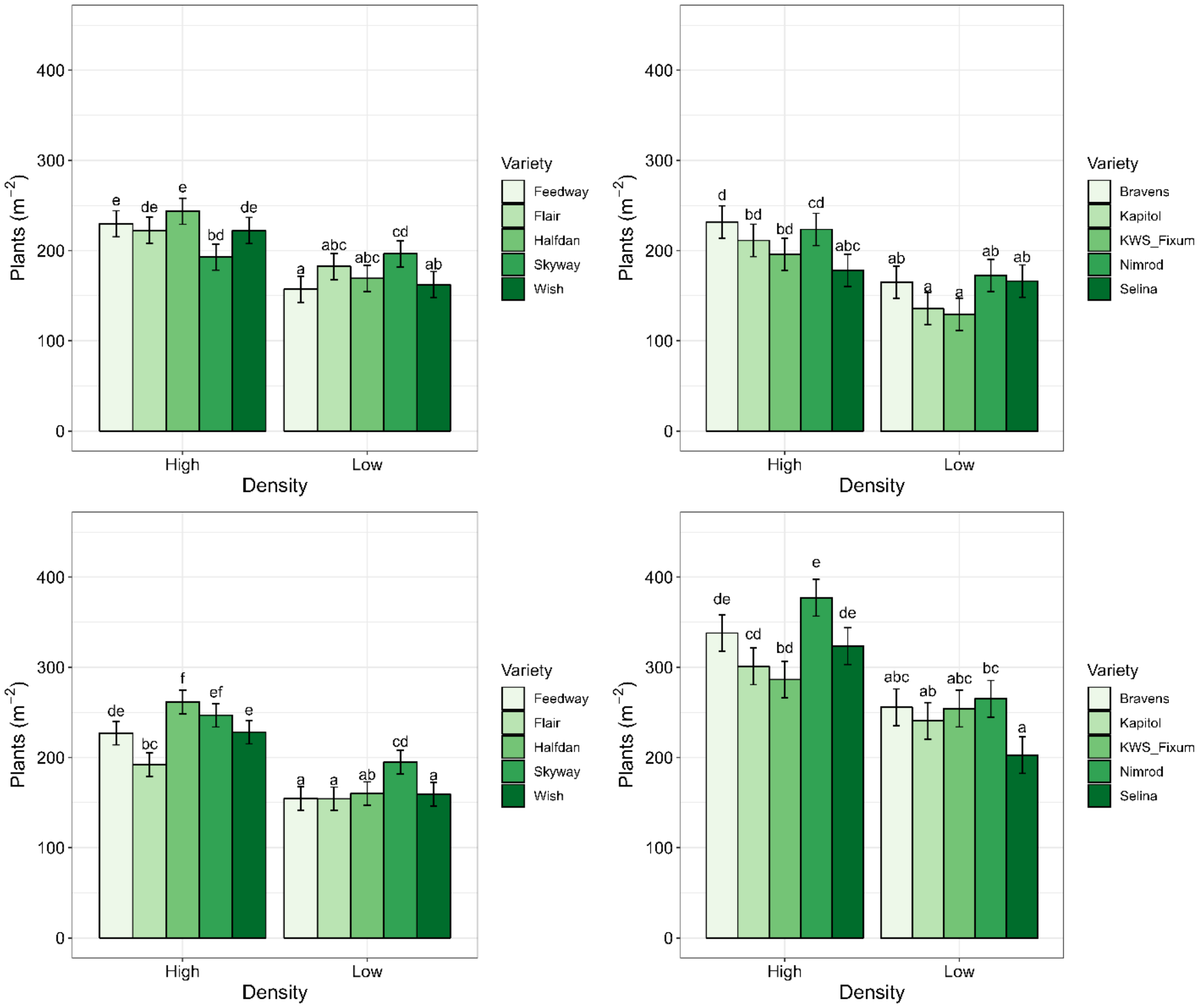

Figure 5: Estimated plant counts per treatment. Error bars represent standard errors. Treatments that do not share any letters were significantly different. Top: Digital plant count based on deep learning. Bottom: Manual plant counts in the field. Left: Barley. Right: Wheat

Figure 5 reports the estimated number of plants per treatment when estimated based on digital and manual plant counting, respectively. While the plot-to-plot correlations between digital and manual plant counts were not that high, the overall conclusions regarding comparisons of plant counts between treatments were similar.

Plant height

Plant height was measured manually in the field at different locations in the plot and digitally from drone images. Correlations between manual and digital plant heights at different times during the growth season is presented in Table 3. Correlations differed according to wind speed at the time of flying and over the season. For wheat, the correlations between digital and manual height measurements were highest at the end of the growing season, while no clear pattern was seen for barley.

Table 3: Pearson correlations between manual and digital plant heights at different times during the growth season.

Date	Barley	Wheat
9/6 – 2023	0.81	0.56
24/6 – 2023	0.12	0.59
7/7 – 2023	0.80	0.76
14/8 – 2023	0.68	0.81

Height growth curves are presented in Figure 6. Height measurements were somewhat affected by high wind speed causing the crop to move, resulting in somewhat lower digital height measurements. For both crops, there was a tendency for the plants to be higher for the low plant density plots but the difference was not significant.

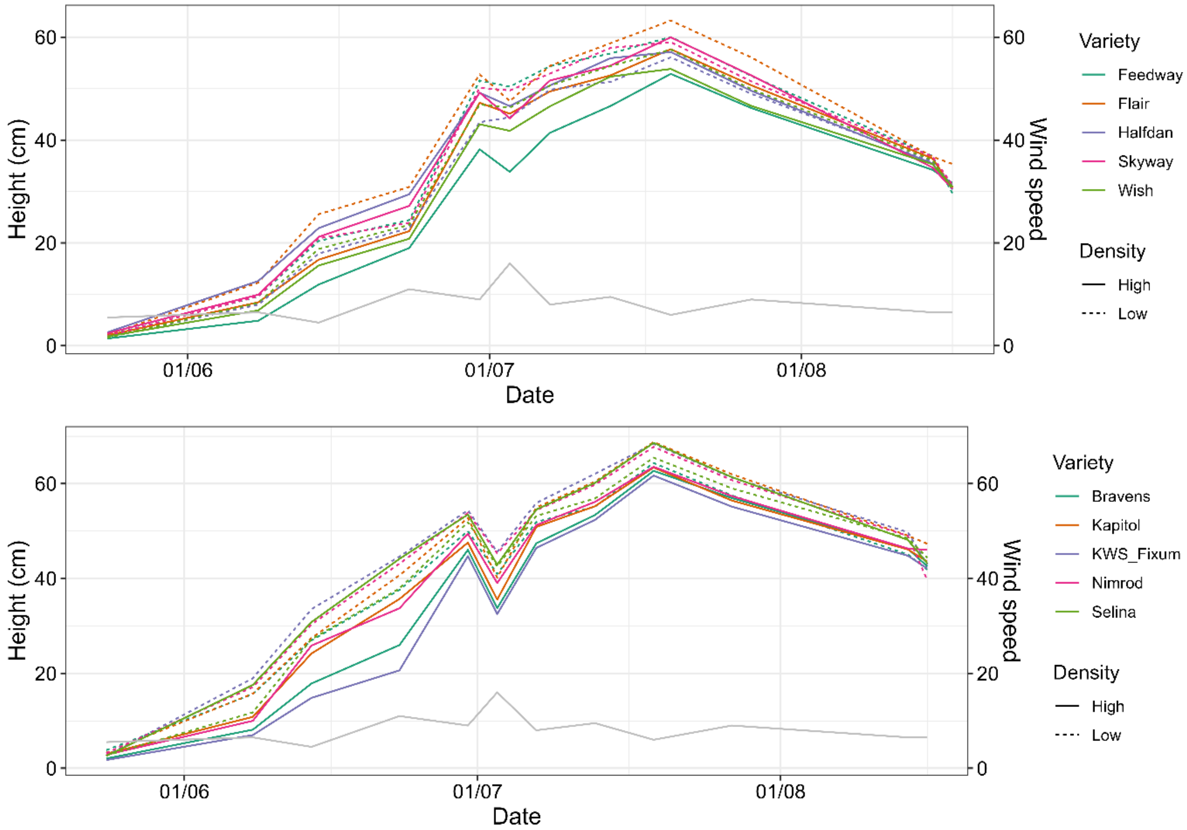

Figure 6: Height growth curves by variety and density in barley (top) and wheat (bottom) based on digital height measurements.

Correlations between plant height (based on digital measurements) and straw yield were higher for wheat than for barley and highest at the end of the growth season near maturity for both crops (Figure 7). Notably, correlations were consistently higher for the digital compared to the manual height measurements.

There was no lodging in any of the two experiments. Accordingly, no digital determination of lodging was possible. However, we suspect that inspection of the height growth curves could be used for revealing lodging.

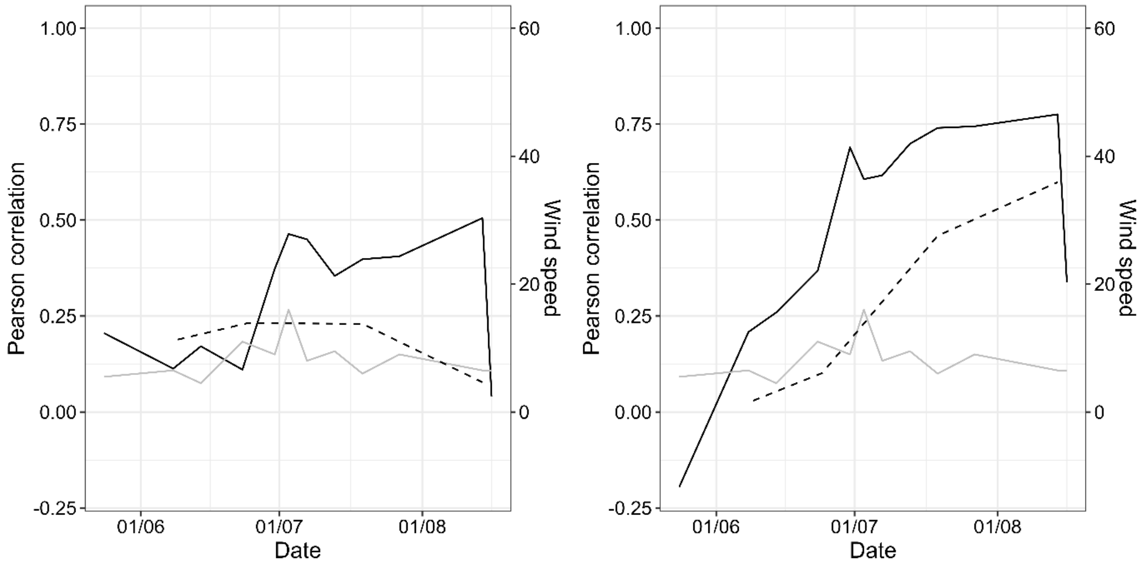

Figure 7: Correlations between straw yield and digital (full line) and manual (dashed line) height measurements, respectively, at different time points during the growth season. Wind speed is illustrated with the grey line.

RBG vegetation indices

Growth curves based on RGB vegetation indices are presented in Figure 8. Cleary, different information about the crop was captured by the different vegetation indices as seen from the different shapes of the growth curves, with the exception being NGRDI and VARI, which were closely correlated giving much the same information.

Correlations between vegetation indices and grain and straw yield at single time points during the growth season are shown in Figure 9. For barley, RGBVI had the highest correlation to the grain yield in the grain-filling period. The correlations to the straw yield were lower compared to the grain yield, but were highest around flowering (for all four indices considered). For wheat, NGRDI and VAR showed the highest correlations to both grain and straw yield around flowering and early grain-filling. Correlations between vegetation indices and grain yield were somewhat higher for wheat compared to barley, whereas correlations between vegetation indices and straw yield were much higher for wheat compared to barley.

As an alternative to the single time-point correlations, the AUVIC was considered (Table 4). VARI and NGRDI again showed indications as potential predictors for both grain and straw yield for wheat.

Table 4: Pearson correlations between grain and straw yield and AUVIC based on different RGB vegetation indices.

	Barley		Wheat	
Variable	**Grain yield**	**Straw yield**	**Grain yield**	**Straw yield**
$AUVIC_{NExG}$	0.47	0.45	0.50	0.53
$AUVIC_{VARI}$	0.51	0.44	0.78	0.71
$AUVIC_{RGBDI}$	0.54	0.33	0.05	0.29
$AUVIC_{NGRDI}$	0.50	0.44	0.75	0.69

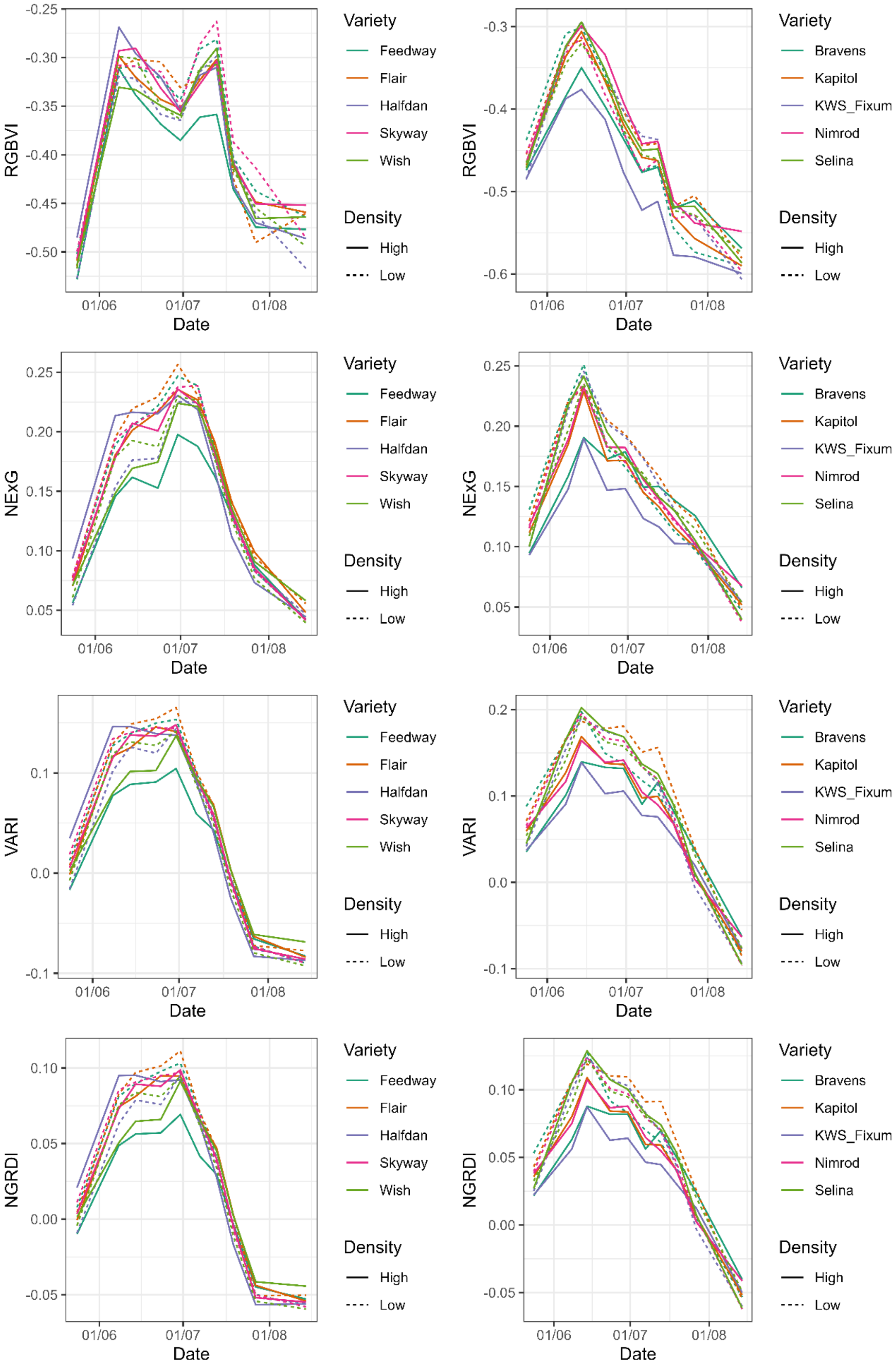

Figure 8: Vegetation index growth curves by variety and density in barley (left) and wheat (right) for different vegetation indices based on RGB images.

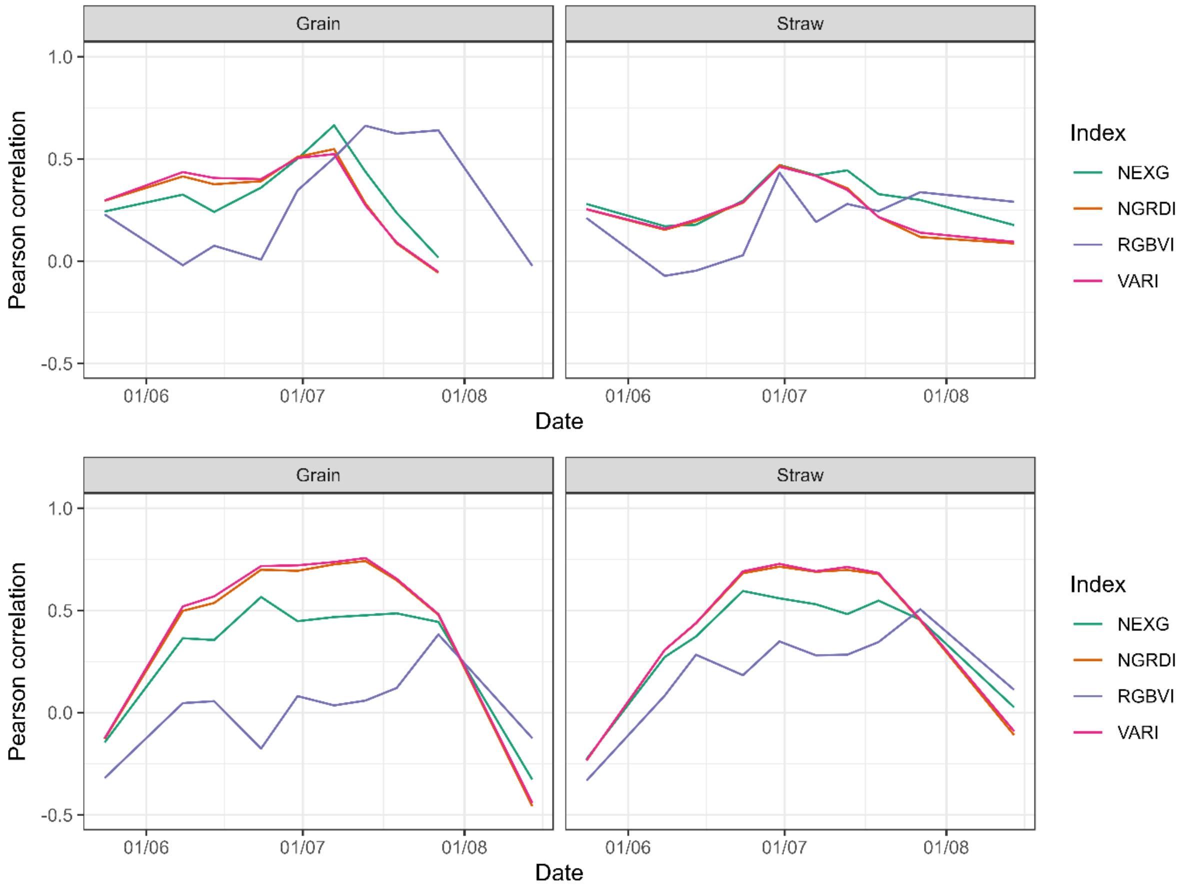

Figure 9: Correlations between different RGB-based vegetation indices and grain and straw yield, respectively, at different time points during the growth season. Top: Barley. Bottom: Wheat.

Multispectral vegetation indices

Growth curves based on vegetation indices from multispectral images are shown in Figure 10. As for the RGB-based indices, different information about the crop was captured by the different vegetation indices as seen from the different shapes of the growth curves.

Correlations between vegetation indices and grain and straw yield at single time points during the growth season are shown in Figure 11. NDVI generally seemed to be the vegetation index with the highest correlation to both grain and straw yield. For both crops, the highest correlations were found during late flowering and early grain-filling. The correlations to the straw yield were lower compared to the grain yield and correlations were much lower for barley compared to wheat.

Correlations between grain and straw yield and AUVIC are shown in Table 5. For barley, AUVIC based on GNDVI showed a higher correlation to grain yield than correlations at any single time point. For wheat, NDVI and NDRE were the most promising indices for AUVIC as a predictor for grain yield, whereas none of the indices showed promising results as predictors for straw yield.

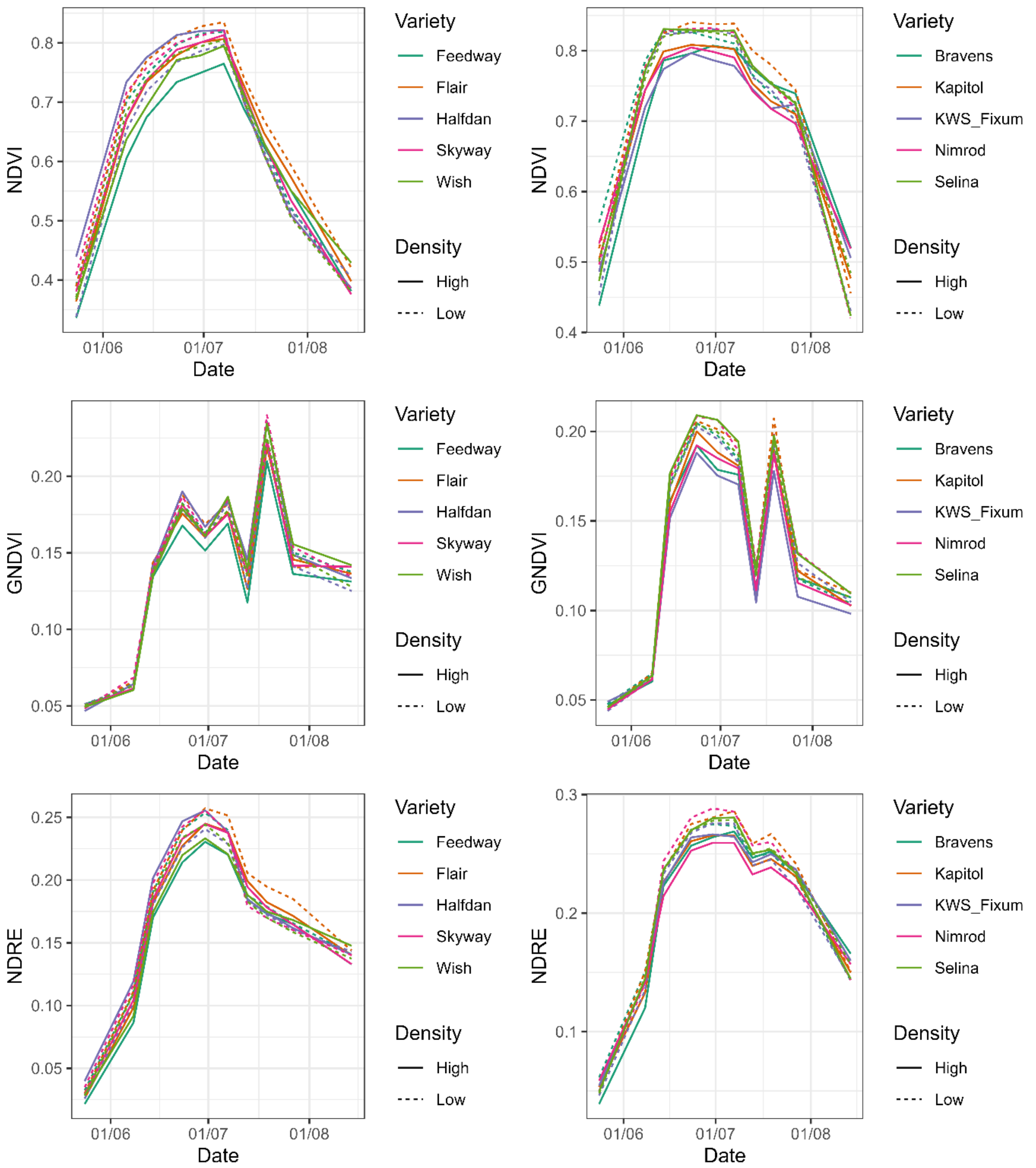

Figure 10: Vegetation index growth curves by variety and density in barley (left) and wheat (right) for different vegetation indices based on multispectral images.

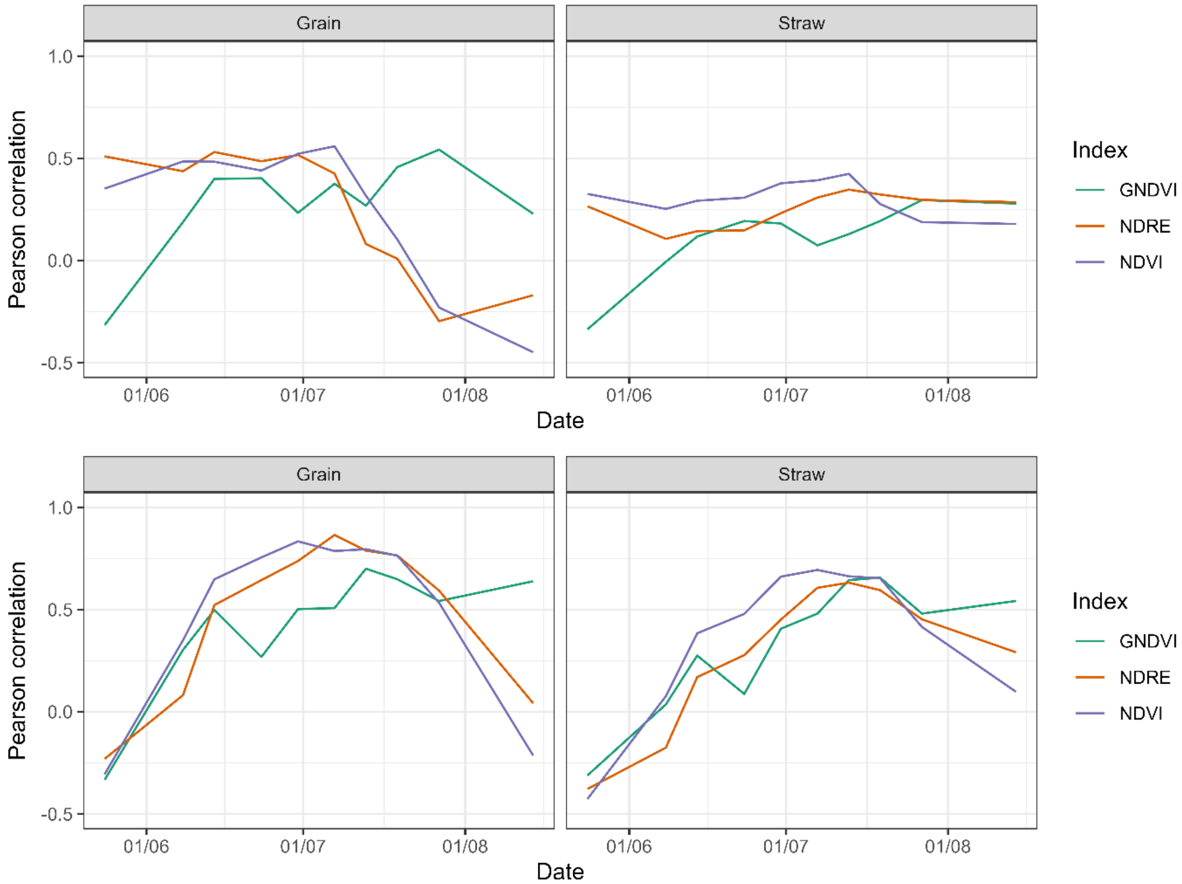

Figure 11: Correlations between different vegetation indices based on multispectral images and grain and straw yield, respectively, at different time points during the growth season. Top: Barley. Bottom: Wheat.

Table 5: Pearson correlations between straw yield and the area under the vegetation index curve (AUVIC) based on different vegetation indices from multispectral images.

	Barley		**Wheat**	
Variable	**Grain yield**	**Straw yield**	**Grain yield**	**Straw yield**
$AUVIC_{GNDVI}$	0.55	0.26	0.65	0.52
$AUVIC_{NDVI}$	0.41	0.48	0.74	0.54
$AUVIC_{NDRE}$	0.41	0.32	0.74	0.46

Prediction models

Different combinations of digital height measurements with RGB or multispectral vegetation indices at single time points, or as AUVIC, were examined as predictors for straw yield with and without adjustment for grain yield (Table 6). For wheat, there was a general tendency that adjusting for grain yield increased the prediction accuracy slightly, whereas the picture was less clear for barley.

Predictions were much better for wheat, reaching prediction correlations of 0.84, than for barley, reaching prediction correlations of 0.51. For wheat, models performed better when predicting the straw yield for new varieties compared to predicting the straw yield for new blocks.

Table 6: Cross-validation (CV) Pearson correlations for different prediction models for straw yield for barley and wheat, respectively. CV was done as 4-fold across blocks, and 5-fold across varieties. The three highest correlations within each crop and cross-validation regime are marked with bold font.

	Barley		Wheat	
Variables	CV by block	CV by variety	CV by block	CV by variety
Height	0.449	**0.484**	0.758	0.820
Height + NDVI	0.409	0.453	0.740	0.819
Height + GNDVI	0.419	0.356	0.761	0.817
Height + NExG	0.383	0.468	0.747	0.819
Height + VARI	**0.497**	0.429	0.726	0.805
Height + GNDVI + NDVI	0.379	0.319	0.729	0.809
Height + NExG + VARI	0.389	0.456	0.727	0.812
Height + $AUVIC_{NDVI}$	0.491	**0.491**	0.738	0.813
Height + $AUVIC_{GNDVI}$	0.436	0.418	0.751	0.810
Height + $AUVIC_{NExG}$	0.449	**0.502**	0.741	0.817
Height + $AUVIC_{VARI}$	0.472	0.462	0.746	0.824
Height + $AUVIC_{GNDVI}$ + $AUVIC_{NDVI}$	0.431	0.428	0.743	0.789
Height + $AUVIC_{NExG}$ + $AUVIC_{VARI}$	0.390	0.409	**0.768**	**0.842**
Grain + Height	0.462	0.458	0.759	**0.835**
Grain + Height + NDVI	0.441	0.445	0.751	0.796
Grain + Height + GNDVI	0.434	0.339	0.749	0.834
Grain + Height + NExG	0.417	0.448	0.740	**0.837**
Grain + Height + VARI	**0.497**	0.435	0.747	0.821
Grain + Height + GNDVI + NDVI	0.415	0.309	0.740	0.786
Grain + Height + NExG + VARI	0.401	0.447	0.734	0.829
Grain + Height + $AUVIC_{NDVI}$	**0.507**	0.476	0.743	0.817
Grain + Height + $AUVIC_{GNDVI}$	0.442	0.425	**0.769**	0.827
Grain + Height + $AUVIC_{NExG}$	0.432	0.465	0.744	0.833
Grain + Height + $AUVIC_{VARI}$	0.466	0.450	0.740	0.819
Grain + Height + $AUVIC_{GNDVI}$ + $AUVIC_{NDVI}$	0.474	0.448	0.753	0.795
Grain + Height + $AUVIC_{NExG}$ + $AUVIC_{VARI}$	0.376	0.403	**0.763**	0.831

For barley, the best model across both cross-validations included height, $AUVIC_{NDVI}$, and adjustment for grain yield.

Barley: Straw yield = -2.40 + 5.05*Height + 0.05*$AUVIC_{NDVI}$ + 0.12*grain yield,

where straw and grain yield were in t/ha, height was the digital height in m measured at the end of the growth season (here 14/8-2023), and $AUVIC_{NDVI}$ was the area under the NDVI growth curve during the entire growth season. While the cross-validated correlation for this model was lower than correlations for some single time points for VARI, this model performed better than the corresponding cross-validated model for VARI alone.

For wheat, the best model across both cross-validations included height, $AUVIC_{NExG}$, and $AUVIC_{VARI}$.

Wheat: Straw yield = 0.31 + 6.88*Height - 0.15*$AUVIC_{NExG}$ + 0.14*$AUVIC_{VARI}$,

where straw yield was in t/ha, height was the digital height in m measured at the end of the growth season (here 14/8-2023), and $AUVIC_{NExG}$ and $AUVIC_{VARI}$ were the area under the NExG and VARI growth curve during the entire growth season, respectively.

Observed vs predicted values of straw yield using the two prediction equations above are presented in Figure 12, revealing the better fit for wheat.

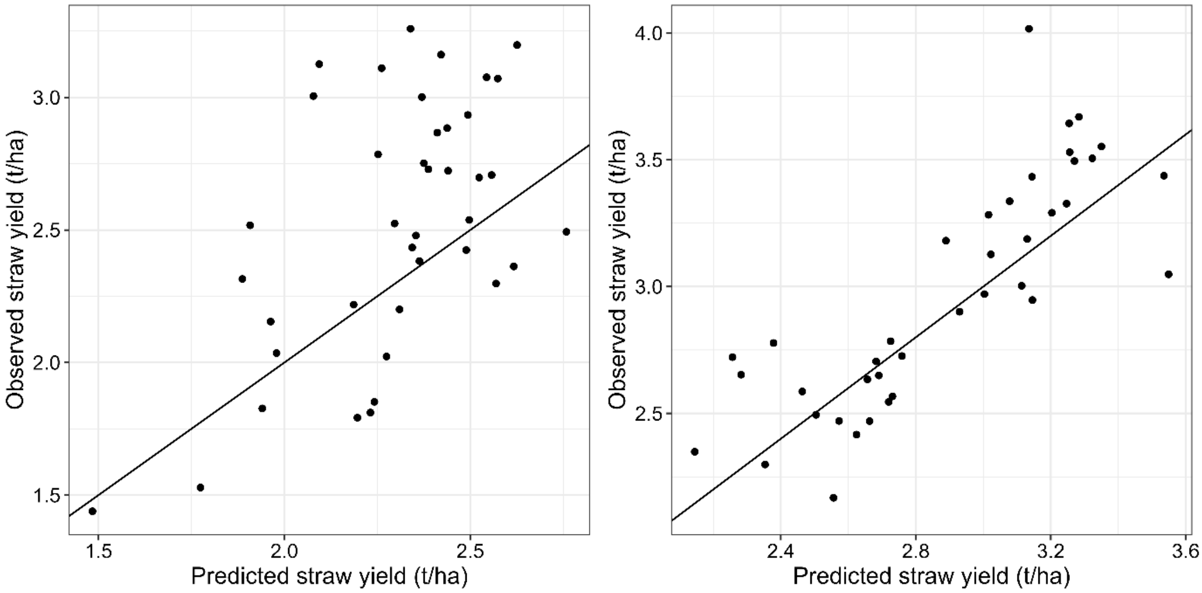

Figure 12: Observed vs predicted straw yield for barley (left) and wheat (right). The line is the one-to-one line indicating a perfect prediction.

Conclusions

Straw yield was better predicted for wheat compared to barley.

Digital height measurements were closer correlated to the straw yield compared to traditional manual height measurements in the field.

For straw yield prediction, there were no clear advantages of using vegetation indices based on multispectral images over RGB images.

While the presented prediction models did include more variables, digital height at the end of the growth season was a decent straw yield predictor on its own.

Results are only for one season only, which may have a high impact on the different coefficients in the presented prediction models. Models that only use one variable, e.g., digital height, may accordingly be a better option for ranking straw yield.