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An Approach to Assess the Impact of High Biaxial Photovoltaic Trackers on Crop Growth and Yield

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Abstract. The growing need for producing renewable energy such as photovoltaic electricity, and the mitigation of the increasing occurrences of heatwaves and drought affecting annual crops, could be addressed by the installation of agrivoltaic systems. Depending on pedoclimatic context, cultivated crop, solar panels technology and implementation configuration, solar panels shading can improve or reduce crop growth and yields. Among photovoltaic installations, solar trackers might have a high development potential. These photovoltaic panels are mounted on a vertical axis at a 7m height. Thanks to their height, their biaxial moving capacity, their small anchoring surface and their punctual structure making plants design easily adaptable to agricultural constraints, they can fit with all types of agricultural systems. The aim of this study was to evaluate the impact of such trackers on crop growth and yields. For this purpose, a set of 6 different fields crop located in western France were studied. Crop phenology, height and yield were investigated. Results showed a delay in crop development near the trackers that was overcome late in the crop cycle, near harvest. For crop height and crop yield, the results showed important spatial variability but without clear trend related to the tracker shadow. The results are discussed in the light of new perspectives, including the consideration of microclimatic and pedological data to better explore the effects of trackers on plant growth and development, the measurement of morphological and physiological traits of plants, the accounting of a multi-trackers effect implemented on the same site, the temporal dynamics of the effect of a tracker.

Keywords: Agrivoltaics, Photovoltaic Tracker, Crop Growth and Yield, Crop Field

1. Introduction

The inexorable global warming partly due to the emission of greenhouse gases forces (i) to develop renewable energy (instead of fossil energy) to meet our energy demand [1] and (ii) to adapt to its effects and especially the agriculture. Solar energy is the most abundant and available energy and is becoming increasingly affordable [2], it thus plays a crucial role for the energetic transition. Agriculture production will suffer from increasing occurrences of high heat and violent weather, which has already led to a 21% drop in productivity in the 20th century [3]. Agrivoltaics could be one the solutions to protect crop production from these global warming effects. Photovoltaic structures installed above crops provide shadows and create microclimates underneath that could benefit to crop production in certain conditions under certain conditions [4].

Many long-standing studies showed that shading negatively affects cereal yields through several mechanisms related to the production and distribution of photoassimilates [5]–[8]. However, the impact of shading on crop fluctuates depending on its intensity and period. The physiological, morphological and phenological responses of plants to shade and the associated microclimate might be highly variable across macroclimatic regions and also across species and even varieties, depending on their light, heat or water needs (e.g. on lettuce [9]) and their dynamics.

Among photovoltaic installations, solar trackers might have a high development potential. Thanks to their height, their biaxial moving capacity, their small anchoring surface, and their punctual structure making plants design easily adaptable to agricultural constraints (figure 1), trackers can fit with all types of agricultural systems, with tractors passages or high solar needs plants. However, the impacts of such tracker, through its installation and its shadow, on crop development and productivity has not yet been evaluated. The aim of this study is therefore to start filling this gap by studying crop phenology, crop height and yield around single trackers.

2. Materials and Methods

This study was located in Brittany and Pays-de-la-Loire, Western France. To evaluate the tracker's effects and especially the effect of its shade, a sampling plan was built up (figure 2) based on the study of single tracker thrown shade and a ratio of the total radiation received at the ground during a year (RR) [10]. Among the six sites selected in this experiment (figure 3) where one relatively isolated tracker was chosen in each, four (1 barley, 1 wheat, 2 maize) were studied for crop phenology and crop height, and six were investigated for crop yield (including 2 other sites in maize).

For the crop development study, the four sites were investigated every two weeks from April to harvest for barley and wheat, and from sowing to harvest for maize. Phenological stages were evaluated and marked using different phenological scales. For barley and wheat, the Zadock scale was used [11], and for maize, the Iowa state university scale was used [12] (table 1). Crop height was measured from the soil to the end of the ear leaf with the use of measuring tape. For each of the 40 sampling points (blue dots on figure 2), ten plants were randomly chosen for height measurement and the average was calculated. Crop yields were measured by sampling and weighing the above ground biomass at harvest in one square meter for each sampling point.

Statistical analysis was performed on grain weights using Generalized linear mixed models (GLMM) in R [13]. Barley and wheat sites were analysed separately, and all 4 maize sites were analysed together. The effect of the sampling points relative positions to the tracker was studied by considering the explaining variables: cardinal axis (North, North-East, East, South-East, South, South-West, West, North-West), distance (5m,10m,15m, 20m and 35m).

3. Results and analysis

3.1 Crop phenology

The crop phenology follow up is shown in figure 4 for the 4 sites and for three observations dates selected among 5 to 9 dates depending on sites: the 1st observations for each site, observation at flowering and right before harvest. For the first observations date, a delay in crop development was observed on each site around the trackers, mostly within 5 meters from the trackers for 2 sites over 4, and even further for the 2 other sites rather N, NE, E directions from the trackers, with some heterogeneities within the fields. This delay was only a few sub-stages for each crop. For example, stages 37 instead of 39 for barley or stage V1 instead of

V2 for maize. At flowering, a delay in crop development was still observed, and rather within 5 or 10 meters from the tracker, with less variability in the rest of the fields. At harvest, the maturity stage was reached in the entire fields even near the trackers, with a slight delay still observable in the barley only within the 5 meters from the tracker.

3.2 Crop height

Height averages for the 4 sites and for each measurement date are presented in figure 5. The flowering date was distinguished on the graphs as used for spatial results observations and analysis. Crop mean height reached almost their maximum around flowering. Results within a site and a date were rather variable, especially for maize. Height averages are represented for all sampled points and for three sampling dates: 1st observation, flowering and harvest, in figure 6. In all sites, important spatial variation from a sampling point to its neighbour made visual interpretations on trackers effects delicate. For barley, crop height in northern points (W, NW, N, NE, E) were greater than southern points (S, SW, SE), even at 5 meters from the tracker. For wheat, the crop in Wand NW axis were higher in the first observation while at flowering or harvest the highest samples were located rather east, south-east, south and close to the tracker in a range of up to 10-15 meters (beyond measurements were not made). Samples were smaller on the SW axis. For both maize sites, crops were smaller at 5 meters from the tracker, rather NE, N, NW directions especially for maize site 1.

3.3 Crop yield

Number of stems, number of ear/cob and grains weight for all 6 sites are presented figure 7. The results showed high variability in the data, also found in the plots not affected by trackers shadows, for all sites. For maize, yields results showed a great spatial variability without clear trend potentially explainable by a tracker effect. For barley and wheat 1, yields were lower at 5 meters from the tracker, especially for wheat N, NE, NW directions. GLMM showed that the explicative variables used for modelling, and related to spatial coordinates, rarely significantly explain the variability of grains weight (table 2), suggesting an important role of other variables not considered yet, and with no regular spatial distribution, probably like soil density, soil granulometry, sowing density, randomness, and not like RR. The R^2 for model built up on all maize together (R^2 of 0.16) was lower than model for individual site (R^2 between 0.33 and 0.57). It was also lower for wheat and maize 2 sites where a second tracker, located south of the studied tracker, projected shadow on the studied area and altered the usual RR spatial distribution obtained with one isolated tracker.

4. Discussion

Crop phenology observations, with height and yield measurements were indirectly compared to RR spatial distribution around trackers. The RR pattern would partly explain phenological results, and possibly crop height results for maize, and crop yields wheat and barley. Some other variables such as soil characteristics, sowing, fertilisation, farming machines passages may have a greater effect and could explain more the data variability.

The development backlog was caught up at harvest for wheat and maize but not entirely for barley. The barley exception could be explained by an early harvest, at the very beginning of crop maturity, leaving no time for the plant to catch up the delay. For crop height, the tracker seemed to have negatively impacted maize in its direct vicinity, positively barley north from the PV structure, and not impacted wheat. This may be due to a higher sensitivity of maize to shadow. Other factors might have important influence on crop. For instance, in wheat the lower height on SW axis may be also explained by the electrical connection (1 meter deep) and the perturbation of soil above. For maize 1, the higher crops north-west from the tracker might be explained by the hedge protection from deleterious solar radiation in the heat waves context occurring in Brittany during July 2022 [14].

Statistical model showed that results were mostly depending on the site, even within a same crop. However, the further implementation of a large number of experimental sites with likely similar crop varieties, field management, and soil and climatic conditions will improve the statistical robustness of the results. In order to better explain agronomic trackers effects and the associated mechanisms, microclimatic and soil data should also be studied, as well as plants morphological and physiological aspect.

The shadows cast by the tracker, have similar effect on crop phenology as observed around trees or next to hedges in agroforestry systems [15]. Further research in this direction could give insight on the radiations levels that could protect from over-irradiation and excessive evapotranspiration without limiting the photosynthesis (i.e. below the light saturation point [16]). The effect on crop phenology raises the question of the effect on grains filing, crop quality, use of nutrients with a fertilisation applied on a supposed homogeneous crop cover.

Here we have studied the effects of a tracker, isolated or partials, knowing that these trackers studied can be installed by dozens to form power plants. This multi tracker configuration raise new important issues, namely whether the effect of these power plants will be cumulative of the effects of each isolated tracker, or whether the effect will be synergistic. The temporal dynamics of the effect of a tracker on crops must also be studied because of the disturbance linked to the installation of a tracker on site. It can be assumed that some of the effects related to ground alterations (excavation of ditches, electrical installations, machinery traffic...) will decrease with time.

5. Conclusion

Crop growth and crop yield were followed on different fields distributed in Brittany and Pays-de-la-Loire. Crop phenology observations showed a delay in crop development caught up at the end of the crop cycle, in the direct vicinity of the trackers. Crop height and yields were highly heterogeneous over the fields and the supposed effect of trackers were hardly observable. Crop height and yields spatial variability was poorly explained by the studied explanatory variables and a larger set of factors, such as pedoclimatic conditions and field management, should be considered to explain the results and identify the tracker effects. Moreover, a larger number of sites should also be studied to reinforce conclusions robustness.

Author contributions

Contributor role	Contributor name
Conceptualization	Clémentine Inghels, Paul-Emile Noirot-Cosson, Annie Guiller, Thomas Kichey
Data curation	Clémentine Inghels
Formal analysis	Clémentine Inghels
Investigation	Clémentine Inghels, Valentine Leroy
Methodology	Annie Guiller, Thomas Kichey, Paul-Emile Noirot-Cosson
Project administration	Clémentine Inghels
Resources	Clémentine Inghels, Paul-Emile Noirot-Cosson, Annie Guiller, Thomas Kichey
Supervision	Clémentine Inghels, Paul-Emile Noirot-Cosson, Annie Guiller, Thomas Kichey
Visualization	Clémentine Inghels
Writing – Original draft preparation	Clémentine Inghels
Writing – Review & Editing	Clémentine Inghels, Paul-Emile Noirot-Cosson, Annie Guiller, Thomas Kichey

Data availability statement

The participants of this study did not give written consent for their data to be shared publicly, so due to the sensitive nature of the research supporting data is not available.

Competing interests

The authors declare no competing interests.

Figures and tables

Figure 1. OKwind high biaxial solar tracker

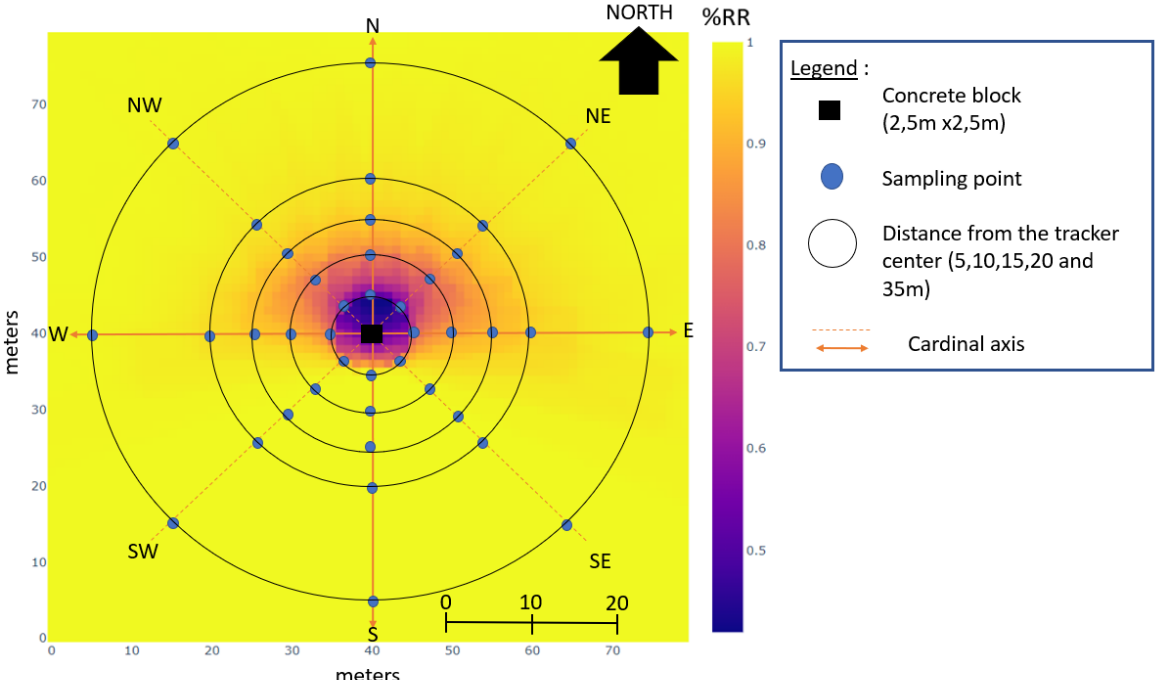

Figure 2. Sampling plan and total radiation received ratio (RR) around a single tracker

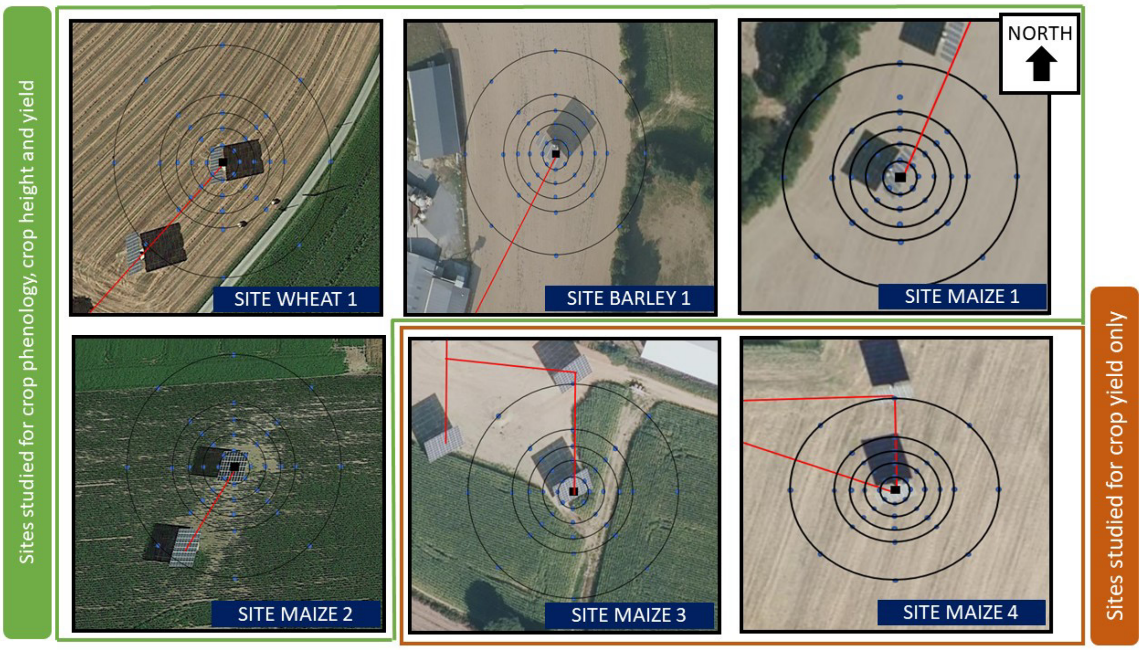

Figure 3. Cartography of each site issued from satellite observation. The red lines represent the electrical connection of the solar trackers. The black rectangle is the tracker'shadow.

Figure 4. Crop phenology at three different dates, 1st observation, flowering and harvest for every sampled point. The scales used are: Zadock scale for barley and wheat, and Iowa state university scale for maize. Values with a blue, yellow or green background represent plots with important, moderate or no delay in crop phenology respectively.

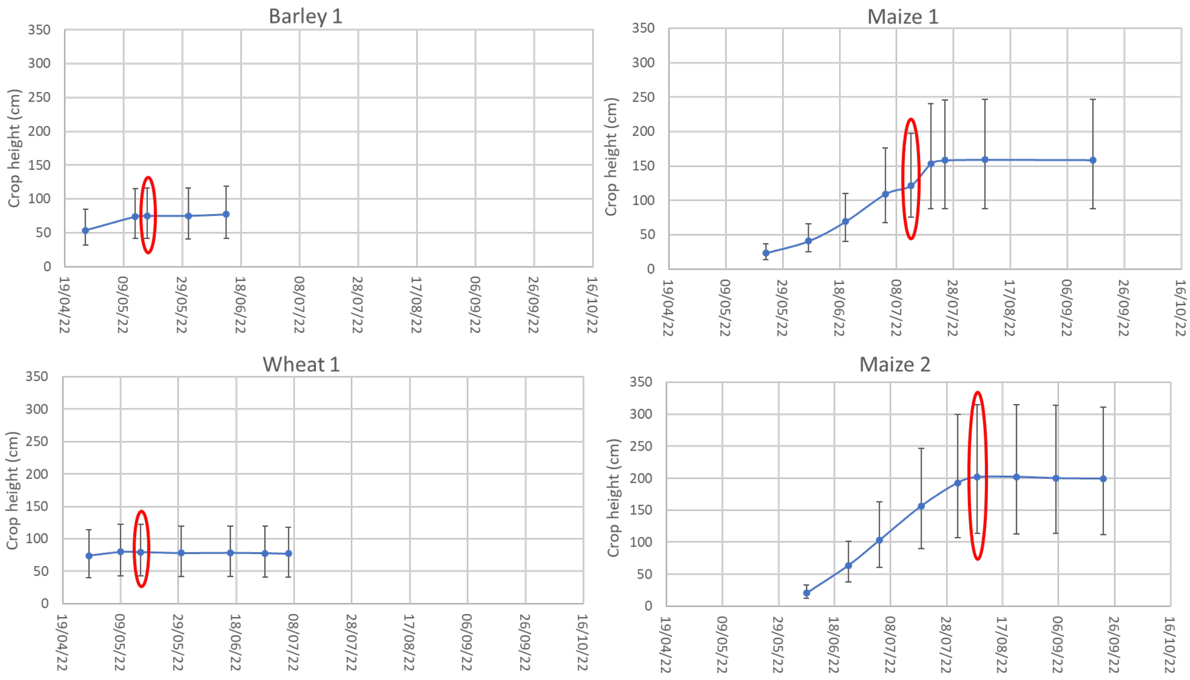

Figure 5. Average crop heights (cm) based on 40 sampled plots for each sampling date at the 4 sites. The red circle indicates flowering date.

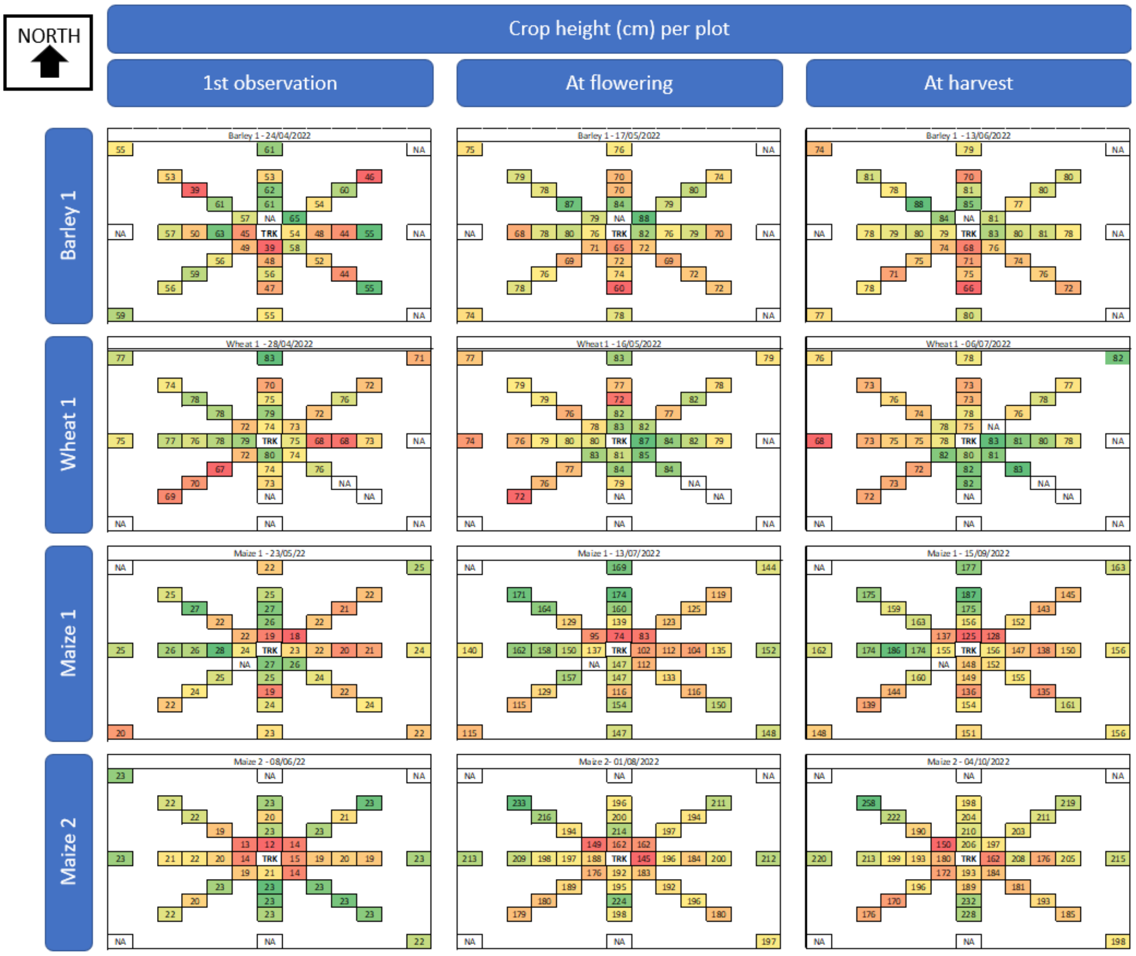

Figure 6. Result for crop height (cm) per plot for each of the 4 development sites, at three dates: 1st observations, flowering and harvest. Results are shown in cm. The color scale from red to green indicate the relative level of each plot crop height to each field and date.

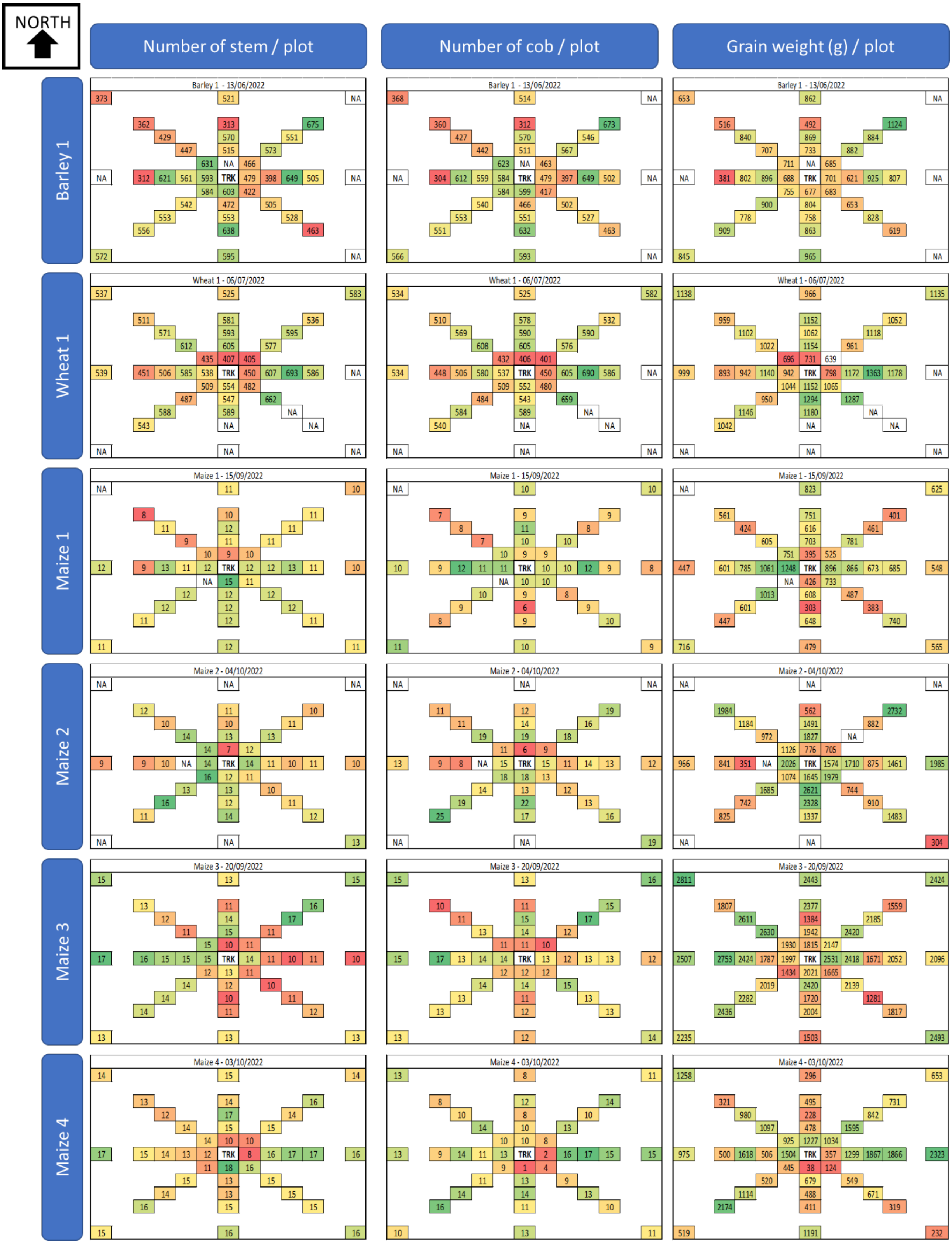

Figure 7. Stem number, ear number and grains weight (in g) for all sites

Table 1. Zadock and Iowa state univesity phenological stages meaning

Zadock‘ scale		Iowa state university’ scale	
Stage number	Related stage category	Stage number	Related stage category
Main stage 3 (30-39)	Elongation of the main stem	Vegetative stages (Vx)	X number of leaf with collar visible
Main stage 4 (41-49)	Ear swelling	Reproductive stages (Rx)	R1: flowering R2-R5: grain development R6: grain maturity
Main stage 6 (61-69)	Flowering		
Main stage 8 (83-89)	Grain maturation		

Table 2. Statistical results of grains weight for each culture. Significance codes: 0 ‘***’;0.001 ‘**’;0.01 ‘*’;0.05 ‘.’ ;0.1 ‘ ’ ;1.

Site	Pr(>F) Axis	Pr(>F) distance	Pr(>F) distance*axis	R^2
Barley 1	0.0509 .	0.0220 *	0.6063	0.5675
Wheat 1	0.5509	0.0335 *	0.5037	0.3335
Maize 1	0.0462 *	0.1621	0.0172 *	0.5292
Maize 2	0.2822	0.7550	0.3009	0.3645
Maize 3	0.8928	0.0088 **	0.1412	0.4923
Maize 4	0.0093 **	0.2241	0.0278 *	0.5410
Maize (4 sites)	0.0479 *	0.9064	0.1509	0.1587

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