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Preliminary Experiment Report

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Abstract

In our agrivoltaics pretrial in Wädenswil, corn salad was grown under and behind ground-based solar modules to study their effects on crop growth. Leaf chlorophyll content, leaf length and width and fresh and dry weight of leaf punches and whole individuals were measured. SPAD values showed significant differences among treatments with the highest values under the modules (51 ± 3) and the lowest behind the modules (47 ± 4a) compared to two control groups (47 ± 3 and 49 ± 3). The cardinal position within the treatment behind the modules showed a distinct reduction in leaf chlorophyll content for the central position ($p < 0.05$). Leaves were significantly longer and wider under the modules at mid-cultivation time and at harvest. Specific Leaf Area (SLA) was highest under and behind the modules and significantly lower in both controls ($p < 0.05$). At harvest, corn salads under modules had the highest fresh weight. Fresh weights of corn salad in both controls and behind the modules were significantly smaller ($p < 0.05$). First results within our pretrial indicate that both beneficial and adverse effects of agrivoltaics on crop growth are possible.

Contents

Introduction

The purpose of this agrophotovoltaics pretrial was to gather first experiences with an agrivoltaic system within our research group and on our campus. It included the planning and installation of nine transparent THEIA solar modules with optical micro-tracking technology from Insolight® and the cultivation and growth analysis of corn salad (*Valerianella locusta* L.).

As land is a rare commodity, the approach of dual land use for energy production and the cultivation of crops or animal husbandry is increasingly gaining socio-political interest in recent times. Concurrently, the combination of arable farming and power generation requires comprehensive know-how in technical as well as agronomic issues in order to find an ideal design for the respective location and the specific use with the different requirements.

Corn salad (or "lamb's lettuce") is a common winter salad in Switzerland. It can be sown directly or planted as a seedling. The duration of its growth until harvest strongly depends on the season and can vary between 4-13 weeks. Corn salad was chosen for cultivation due to its temporal flexibility of growth, the possibility to compare multiple rounds of cultivation in different seasons and its low height, which suits the experimental design with ground-based solar modules. This report presents the results of the first run with corn salad.

Materials and Methods

Experimental site and design

Nine THEIA-cSi (Translucency & High-Efficiency In Agrivoltaics crystalline silicon) photovoltaic modules from Insolight® were installed on 8 November 2021 on the campus of the ZHAW. The solar modules were mounted between 0.6 and 1.6 m above the ground in a 3 x 3 arrangement (covering an area of 3.50 x 1.5 m). A detailed installation scheme can be found in the appendix. The modules were put into operation on 10 November. The MLT-mode (Maximum Light Transmission), in which according to the manufacturer up to 70% of the incident light are transmitted, was chosen for all modules during the whole growth season due to the shortened daytime in winter.

As the area was previously a meadow, approximately 30 cm of the grassy soil was removed and filled with mixed substrate of extensive rooftop garden soil and peat-free potting soil (one part each). 1788 individuals of organic corn salad seedlings ('Princess') were planted 11 November on two areas of approximately 3.50 x 3 m within a perforated foil with a 10 x 12 cm spacing, 2 m apart from each other (Fig. 1). The solar modules covered an area of 2 x 3.5 m which was further divided into three subplots ("M West", "M central" and "M East") with 48 salads per subplot (0.6 m^2) exclusive of the outer 3-4 rows of salads (i.e. 30-40 cm) to avoid border effects. Likewise, the area North of the modules ("Mb"), which is shaded but not covered by the modules, and the two control areas ("C1" and "C2") were divided into three subplots (West, central, East) each.

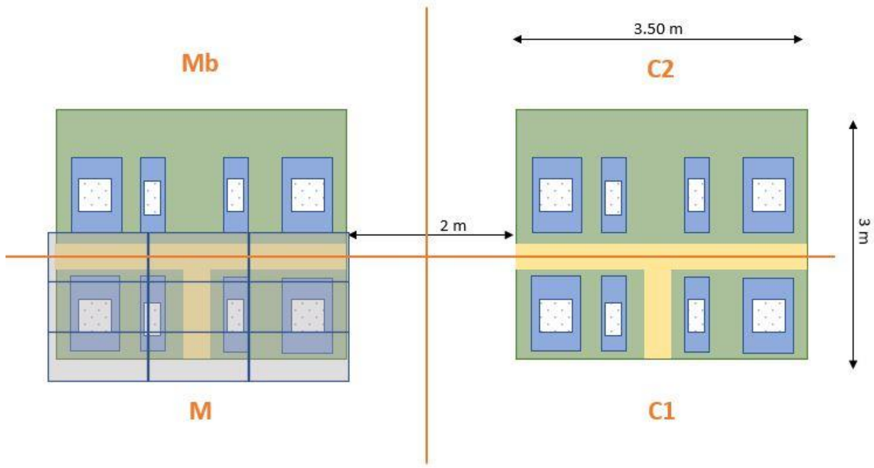

Fig. 1: Schematic representation of the experimental design at the Grüental pretrial site. The green areas represent the area planted with corn salad where at the left side, on the bottom, the solar modules were mounted. The smaller blue areas embody the actual plots where measurements were taken (SPAD) with most measurements (leaf length and width, weights) being taken from the central part of the plot (dotted white area). The yellow bars are the wooden planks needed to be able to reach the plants within the central part of the plot.

Leaf chlorophyll content

Leaf chlorophyll content was compiled eight weeks after planting (7 January 2022) by usage of a chlorophyll meter (SPAD-502Plus Konica Minolta®). In every subplot the youngest fully developed leaf of 30 individual corn salads was measured, taking care making efforts to place the sensor head in the same way each time. Measurement order was kept the same for all plots to allow an assignment of position within the West-East transect.

Leaf length and width

In each subplot, one leaf per individual was chosen of in total six individual corn salads with the same positions. The width of each leaf was measured with a caliper 7 January. At harvest (8 February) three leaves per salad were taken and their length and width measured.

Leaf punches (SLA and weights)

As the area of the leaf punches was known, specific leaf area (SLA) was calculated by dividing the area by the dry weight. The same leaves which were collected for measuring leaf width were punched with a metal puncher (diameter: 12 mm) at the same position directly before weighing the fresh weight. The punches were then put in a plastic bag with soaked cotton overnight (20 hours) and thereafter their saturated weight was measured. Thereafter the leaf punches were put in paper bags and dried for 48 hours at 80°C in an oven to obtain their dry weight.

Harvest

After close to 13 weeks (8 February) eight individual corn salads at central positions within each subplot were harvested, washed and weighted (96 in total). The samples were then put into separate paper bags and dried for 48 hours at 80°C to obtain their dry weight.

Statistical analysis

Statistical analyses were carried out with R version 3.6.1. The data was tested for normality and homogeneity of variance by the Shapiro–Wilk test and a visual inspection of residuals. Differences in group means among groups was analysed by a multifactorial ANOVA (type I, sequential sum of squares). Significances of each factor were assessed by means of the F-test. Statistical modelling was performed with several linear models, following the pattern of response variable ~ treatment*treatment position For post-hoc analysis a Tukey test was used to compare the means of treatment groups with the HSD.test()-function within the R agricolae package (de Mendiburu 2020) with a significance threshold of $\alpha = 0.05$.

Results

Chlorophyll content

The results of SPAD-measurements are summarized in Fig. 2. SPAD values were normally distributed except for treatment “M” (under modules) which was negatively skewed. Comparison of SPAD values among treatments showed significant differences among treatments with the highest values under the modules (51 ± 3c) and the lowest behind the modules (treatment “Mb”) (47 ± 4a) (Fig. 2a). The difference between the front (“C1”, 47 ± 3a) and back control (“C2”, 49 ± 3b) was also significant ($p < 0.05$). A further consideration of the cardinal direction within each treatment (Northwest “NW”, “central”, Southeast “SE”) shows a distinct reduction in leaf chlorophyll content for the central position behind the modules (Fig. 2b). Visualizing SPAD values of individual salads along the NW-SE transect shows a slight decline in the central part (Fig. 2c) which is particularly pronounced in the Mb treatment (Fig. 2d).

Leaf length and width

Leaves were significantly longer and wider under the modules at both measurement times (8 and 13 weeks after planting) (Tab. 1). In mid-cultivation time leaves in the treatment behind the modules were smallest, at harvest time their size was between that of the two control groups.

Leaf punches (SLA and weights)

Treatment had a significant effect on fresh and dry weight and thus SLA of leaf punches ($p < 0.001$). SLA of leaf punches was highest under and behind the modules and significantly lower in both controls (Tab.

2). The punches of C1 had the highest fresh and dry weight, the fresh weights and dry weights of M and Mb were significantly lower. The saturated weights showed a relatively high standard variance and no significant differences between any treatments.

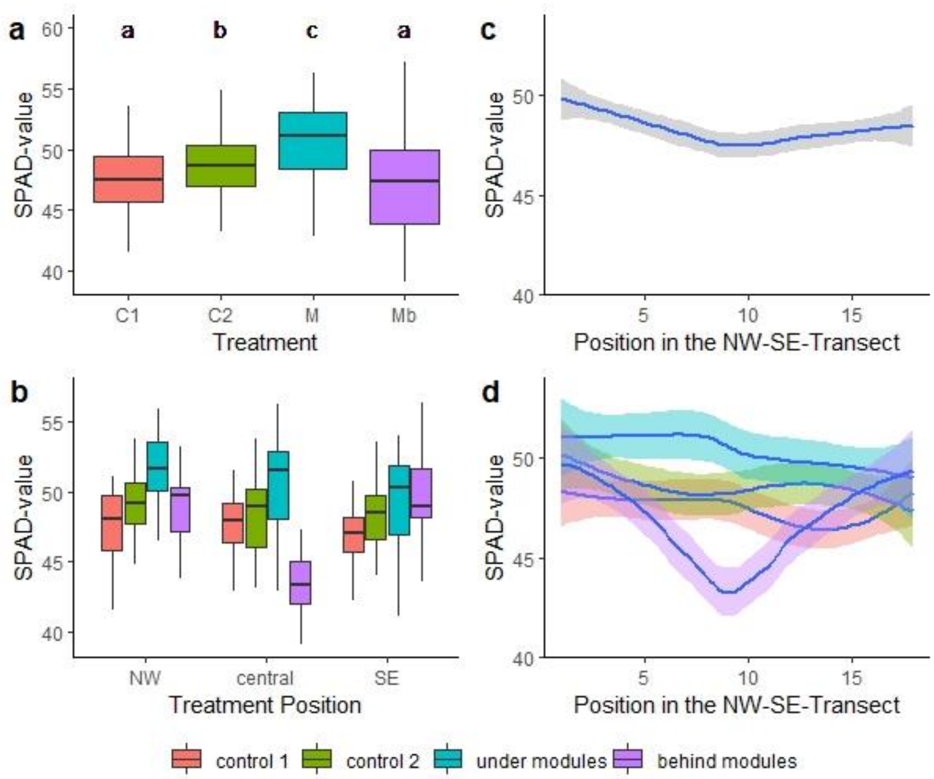

Fig. 2: Summary of leaf chlorophyll measurements (SPAD) on corn salad. (a) Boxplots comparing differences in SPAD between treatments where small letters indicate significant differences (p < 0.05). (b) Visualization of differences between and among subplots under consideration of their cardinal direction. (c) SPAD values of individual salads along the NW-SE transect for all measurements. (d) SPAD values of individual salads along the NW-SE transect for all measurements within each treatment.

Tab. 1: Summary of leaf length and width measurements, taken at two different time points (8 and 13 weeks after planting). Given are means with their standard deviation. Small letters indicate significant differences (p < 0.05).

	8 weeks after planting	**13 weeks after planting (at harvest)**	
Treatment	Leaf width [mm]	Leaf width [mm]	Leaf length [mm]
C1	19.9 ± 1.2ab	24.3 ± 1.6c	44.7 ± 5.8c
C2	19.8 ± 1.2ab	26.1 ± 1.4bc	52.6 ± 3.2b
M	20.4 ± 1.1a	30.7 ± 1.8a	63.2 ± 4.0a
Mb	18.8 ± 1.1b	26.1 ± 1.6b	51.8 ± 3.2b

Tab. 2: Summary of the specific leaf area (SLA) of leaf punches and their fresh, saturated and dry weights. Given are means with their standard deviation. Small letters indicate significant differences (p < 0.05).

	8 weeks after planting			
Treatment	SLA	Fresh weight [g]	Saturated Weight [g]	Dry Weight [g]
C1	24.8 ± 1.4c	39.3 ± 1.6a	51.5 ± 4.5a	4.6 ± 0.3a
C2	27.2 ± 1.8b	37.5 ± 2.0b	48.7 ± 6.2a	4.2 ± 0.3b
M	29.6 ± 1.6a	36.3 ± 1.5b	53.1 ± 6.7a	3.8 ± 0.2c
Mb	28.8 ± 2.4a	36.6 ± 2.6b	50.8 ± 6.0a	3.9 ± 0.3c

Harvest

Corn salads under modules had the highest fresh weight (Fig. 3a). Fresh weights of both controls and corn salads grown behind the modules were significantly smaller ($p < 0.05$). Regarding their dry weights, no differences were found between treatments M and Mb and the controls (Fig. 3b). Corn salad leaves were longest and widest in the M treatment (Fig. 3c and Fig. 3d), being significantly longer than those of the controls and the Mb treatment.

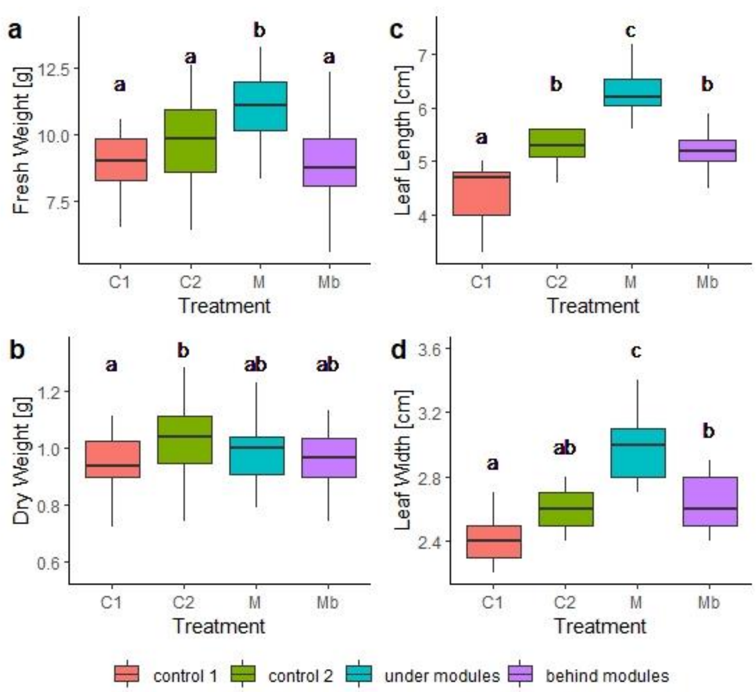

Fig. 3: Summary of measurements taken at harvest of corn salad. Comparison of (a) fresh weight, (b) dry weight, (c) leaf length and (d) leaf width. Letters indicate significant differences (p < 0.05) between treatments.

Tab. 3: Summary of the fresh and dry weights at harvest. Given are means with their standard deviation. Small letters indicate significant differences ($p < 0.05$).

	13 weeks after planting (harvest)	
Treatment	Fresh weight [g]	Dry weight [g]
C1	9.0 ± 1.1a	0.94 ± 0.11a
C2	9.8 ± 1.5a	1.04 ± 0.13b
M	10.9 ± 1.4b	0.98 ± 0.11b
Mb	8.9 ± 1.5a	0.96 ± 0.15ab

Energy production

Total produced energy from 11 November 2021 to 8 February 2022 (90 days) amounted to 20962 Wh in total (with a mean of 209 ± 180 Wh).

Discussion

Several measured parameters of this small pretrial experiment indicate that the solar modules had a positive influence on growth of corn salads located directly under the solar modules but a slightly negative one on plants situated behind the modules. More precisely, SPAD measurements showed highest values of leaf chlorophyll content in salads under the solar modules and lowest values in salads behind the solar modules. Leaf length and width was higher under the modules throughout the growth period while plants behind the modules, which had the smallest leaves in mid-cultivation time, seemed to have caught up later in their development. At harvest, corn salads under the solar modules had the highest fresh weight. Corn salads behind the solar modules were lowest but the difference to both control groups was not significant. In total, the crops under the solar modules benefited from the environment created by the modules. This advantage could have occurred due to the retention of ground radiation or the clearance from snow cover. It can be theorized that these possible beneficial effects on the microenvironment were not present in the zone behind the modules. Hence, assumably in the lack of positive environmental influences the adverse reduction in light availability reduced corn salad yield.

The small area of the nine solar modules created a minor area of direct shading which, furthermore, was subjected to pronounced daily shifts of shade due to the winter sun's low angle (see appendix). The significantly different SPAD values between the front and back control give evidence for a non-homogenous environment within the control which can probably attributed to light availability. Analysis of the subplot position within one treatment showed a distinct reduction for the central position behind the modules which was confirmed by the visualization of SPAD values of individual salads along the NW-SE transect with a particularly pronounced decline in the Mb treatment.

Surprisingly, the punches of C1 had the highest fresh and dry weight, with the fresh and dry weights of M and Mb being significantly lower. This cannot be explained by the available data. Possibly, corn salads needed time to adapt to the microclimate under the modules in the beginning (after planting) and only later profited from it.

Interestingly, SLA of leaf punches was highest under and behind the modules and significantly lower in both controls. As SLA is the leaf area divided by its mass, SLA allows an estimation of leaf thickness. In our experimental study, the significantly higher SLA of leaves in the M and Mb treatment could be interpreted as a shade-induced reaction (Gommers et al. 2013). However, there is a difference in SLA calculate for whole plants or for single leaves, the latter varying with leaf position and with leaf age, the former with plant age (Gunn et al. 1999). As care was taken to choose leaves of the same age, our results should still be a good estimate of SLA. Thus, it appears that the corn salads grown under shade showed shade-induced reactions by developing larger but thinner leaves.

Conclusion

Agrivoltaics systems face several challenges to optimize energy and plant production. Our pretrial focused solely on the agronomic aspect and showed that solar modules could exert a positive influence on crop growth through a beneficial microenvironment. However, as our first results with corn salad indicated, solar modules can also reduce yield if those positive environmental influences are not present. A thorough understanding of the created environment seems to be necessary to achieve an ideal dual land use.

References

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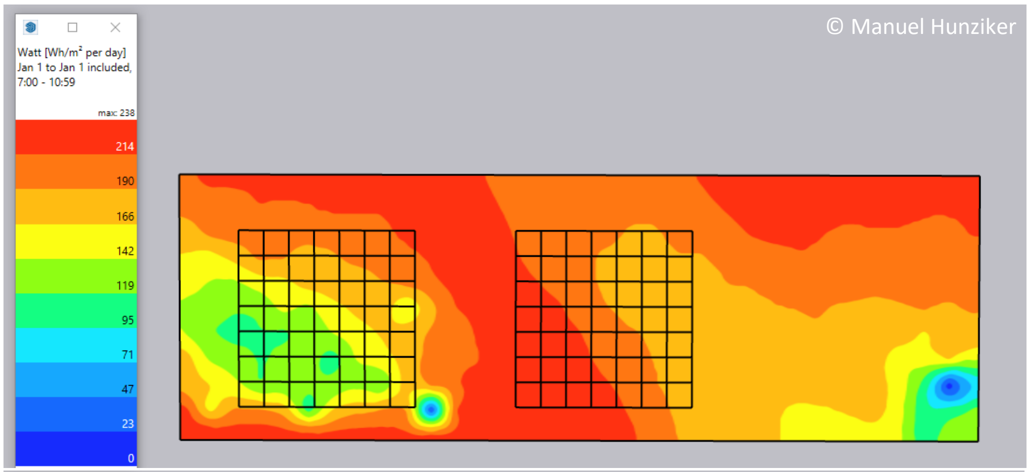
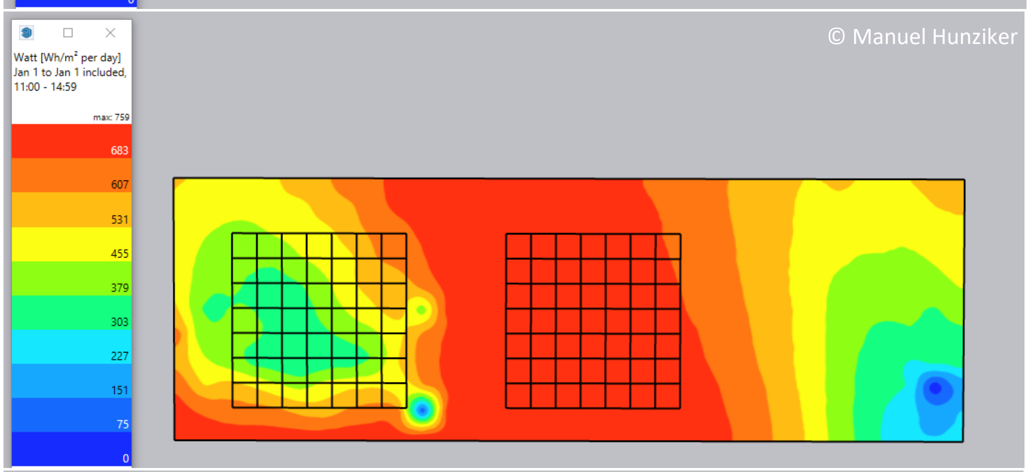
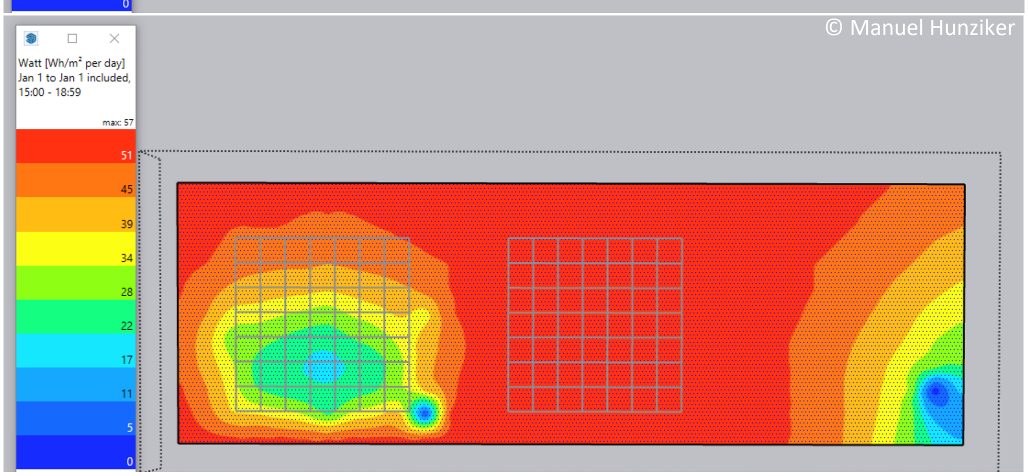
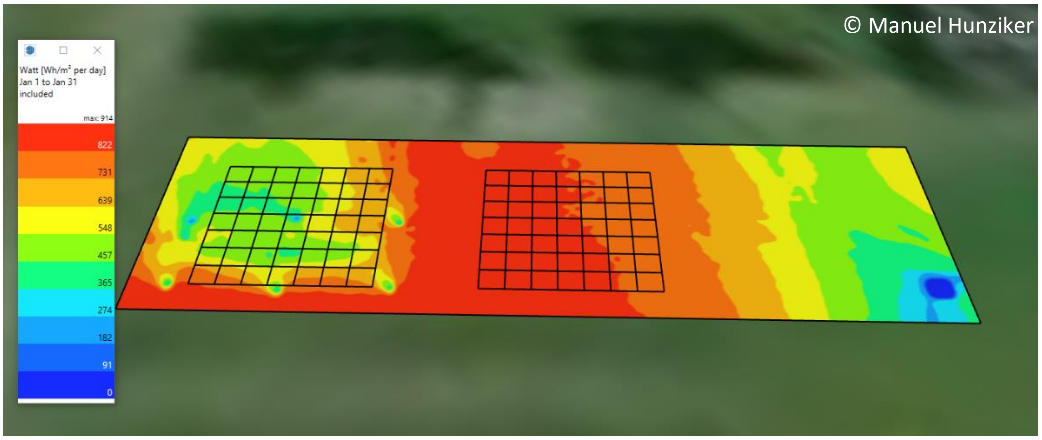
Appendix

Below four graphs modelling direct solar radiation (Wh m^{-2}) are presented. The time duration (7 to 10:59 am, 11 am to 2:59 pm and 3 to 7 pm) is readable at the left side in the top white box (first three graphs). The last graph shows the daily mean for January.









Below four pictures give visual impressions of the pretrial.