

Drone-based sorghum height estimation and plant modeling

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1 Introduction

Sorghum is an important crop for food production in hot and dry climates, particularly in Africa, due to its ability to withstand drought and heat. However, further research is needed to improve the yields in these harsh environments. To achieve this, plant genetic researchers must conduct experiments to optimize sorghum cultivars. If a plant model can be developed to predict growth in African breeding environments, it would be possible to increase yields in these areas.

One of the critical factors that influence sorghum yield is its height. Therefore, by monitoring the plant's height over time, researchers can determine its growth rate and predict yield. However, sorghum height varies depending on the variety and growth conditions. So, considering various treatment combinations, frequent measurement of sorghum height is necessary to investigate treatment effects on growth rate.

To measure sorghum height, researchers can use Structure from Motion technology to predict the crop's 3D shape and then measure its height. Drones can be handy for this purpose, as they can provide high-throughput measurements more frequently than manual measurements taken on the ground. In this paper, we will use drones to measure the height of summer sorghum crops and develop and verify models for sorghum keys and Growing Degree days.

2 Methods

2.1 Experimental Site

The UC Davis experimental field was the site of a sorghum experiment conducted by the Diepenbrock lab in the summer of 2022. Specifically, the sorghum crop was well-suited for the dimensions of a field located south of the sheep barn, which spanned 265 feet from east to west and 45 feet from north to south. The field comprised 18 beds, each 45 feet long, and was arranged into 18 rows. The outer edges of the sorghum field were composed of border crops, as shown in Table 1.

Table 1: Field map for the Sorghum experiment

ft	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
12.5	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
15	B	B	3112	3112	3111	3111	3110	3110	3109	3109	3108	3108	3107	3107	3106	3106	B	B
15	B	B	3099	3099	3100	3100	3101	3101	3102	3102	3103	3103	3104	3104	3105	3105	B	B
15	B	B	3098	3098	3097	3097	3096	3096	3095	3095	3094	3094	3093	3093	3092	3092	B	B
15	B	B	3085	3085	3086	3086	3087	3087	3088	3088	3089	3089	3090	3090	3091	3091	B	B
15	B	B	3084	3084	3083	3083	3082	3082	3081	3081	3080	3080	3079	3079	3078	3078	B	B
15	B	B	3071	3071	3072	3072	3073	3073	3074	3074	3075	3075	3076	3076	3077	3077	B	B
15	B	B	3070	3070	3069	3069	3068	3068	3067	3067	3066	3066	3065	3065	3064	3064	B	B
15	B	B	3057	3057	3058	3058	3059	3059	3060	3060	3061	3061	3062	3062	3063	3063	B	B
15	B	B	3056	3056	3055	3055	3054	3054	3053	3053	3052	3052	3051	3051	3050	3050	B	B
15	B	B	3043	3043	3044	3044	3045	3045	3046	3046	3047	3047	3048	3048	3049	3049	B	B
15	B	B	3042	3042	3041	3041	3040	3040	3039	3039	3038	3038	3037	3037	3036	3036	B	B
15	B	B	3029	3029	3030	3030	3031	3031	3032	3032	3033	3033	3034	3034	3035	3035	B	B
15	B	B	3028	3028	3027	3027	3026	3026	3025	3025	3024	3024	3023	3023	3022	3022	B	B
15	B	B	3015	3015	3016	3016	3017	3017	3018	3018	3019	3019	3020	3020	3021	3021	B	B
15	B	B	3014	3014	3013	3013	3012	3012	3011	3011	3010	3010	3009	3009	3008	3008	B	B
15	B	B	3001	3001	3002	3002	3003	3003	3004	3004	3005	3005	3006	3006	3007	3007	B	B
12.5	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B

2.2 Drone data acquisition

2.2.1 Drone Specification

We used a DJI Phantom4 Pro drone to obtain aerial images of the Sorghum field. Table 2 shows the Phantom 4 Pro drone specification.

Table 2: DJI Phantom 4 Specifications

Aircraft	Specifications
Weight (Battery and Propellers Included)	1380 g
Diagonal Size (Excluding Propellers)	350 mm
Max Speed	45 mph (72 kph) in Sport mode
Max Service Ceiling Above Sea Level	19685 feet (6000 m)
Max Flight Time	Approx. 28 minutes
Operating Temperature Range	32° to 104°F (0° to 40°C)
GPS	GPS/GLONASS
Camera	Specifications
Sensor	1/2.3" CMOS, Effective pixels: 12.4M
Lens	FOV 94°
ISO Range	100-3200 (video), 100-1600 (photo)
Shutter Speed	8s - 1/8000s
Max Image Size	4000×3000

2.2.2 Drone Flight

The drone flight path was generated through the Mission Planner, converted into a CSV file, and transmitted to the Litchi software. The Litchi software sends a waypoint to the drone, automatically flying 5m above ground level (Figure 1). Table 3 shows the drone flight logs.



Figure 1: A figure showing the drone flight path

Table 3: Number of images captured on each date

Date & Time	# of Images
6/24/22 11:39 AM	874
7/1/22 10:23 AM	460
7/8/22 10:24 AM	994
7/15/22 10:20 AM	492
7/22/22 10:11 AM	408
7/29/22 11:14 AM	493
8/2/22 10:22 AM	492
8/5/22 10:23 AM	854
8/12/22 10:11 AM	410
8/26/22 10:08 AM	492
9/2/22 10:26 AM	492

2.3 Drone Data Processing

2.3.1 Structure from Motion Processing

Metashape 1.8.6 was used to process acquired drone data. It was processed using a workstation with i7-4930K CPU (6 cores), 64GB RAM, and RTX A5000 (24GB) GPU and took approximately 3 hours to process per day. The GCP marking process was performed manually by looking at the image, and the rest of the work was automatically performed through the batch process. The processes obtained ortho-mosaiced RGB images and a digital elevation model.

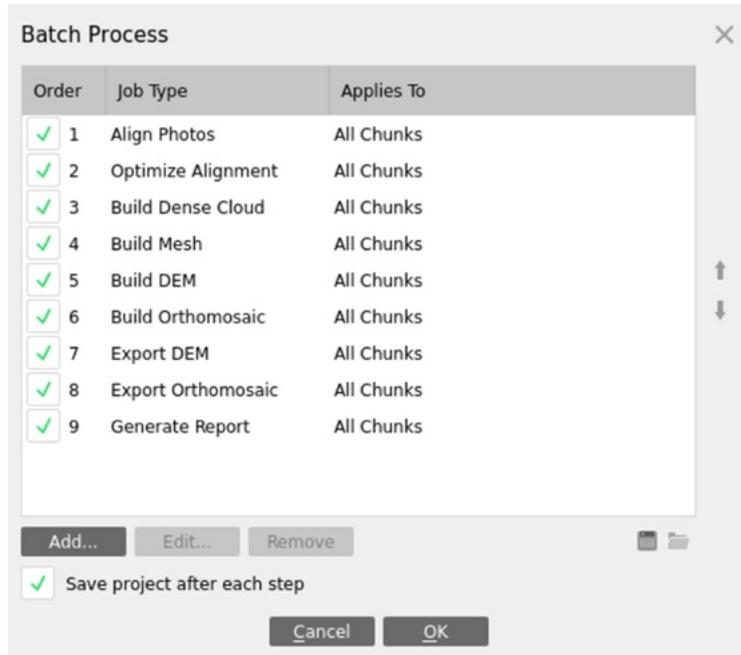


Figure 2: Batch Process Tasks for the Metashape Processing

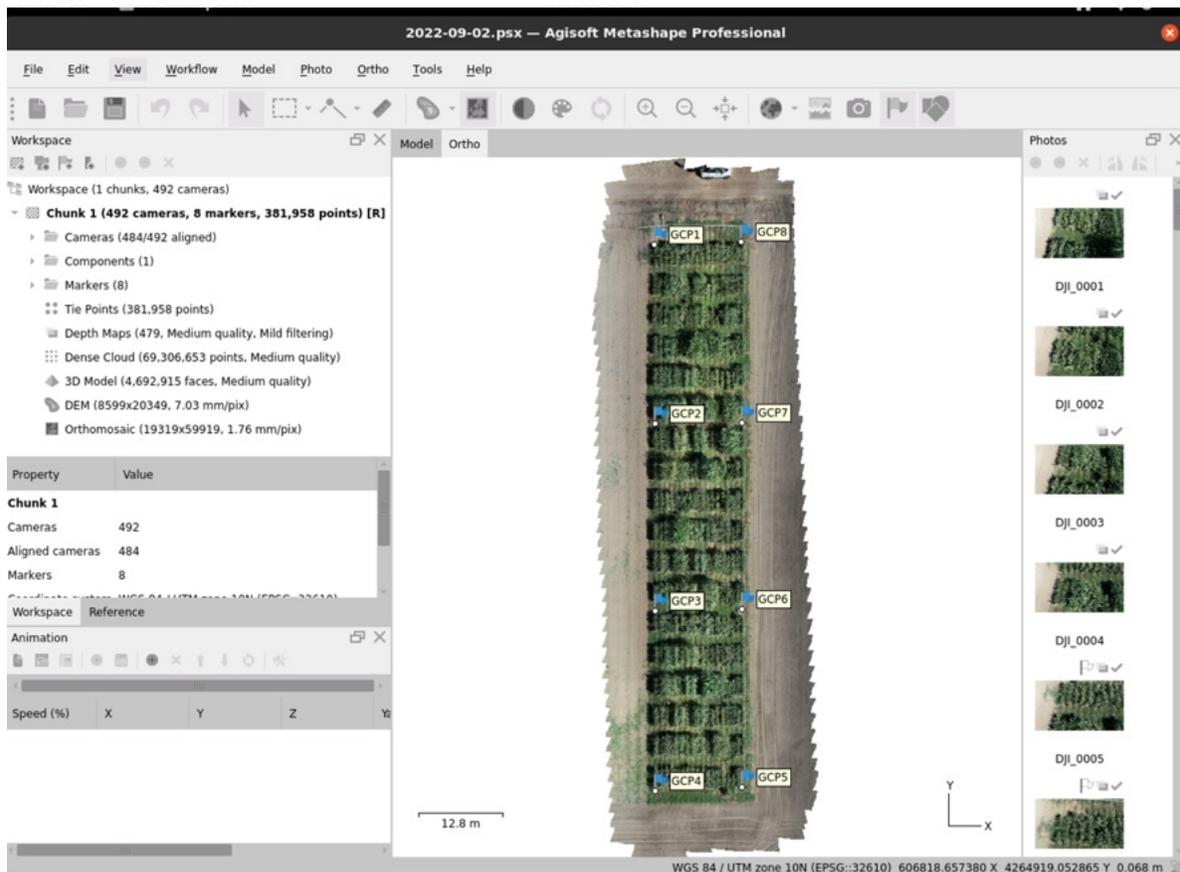


Figure 3: An example result of Metashape Processing

2.3.2 Extract Sorghum Plant Height from the Digital Elevation Model

The extracted digital elevation model was analyzed through Python 3.8. The python script used the gdal package to get the value of the image by calling the tif file. Referring to the field partition in Table 1, the Digital Elevation Model was divided into sections. Next, the cumulative probability distribution was calculated, and the values corresponding to the top 99% were extracted and recorded as the height of the sorghum. Except for Border crops, there was a total of 112 genotypes with two replicates, so 224 plots were analyzed.

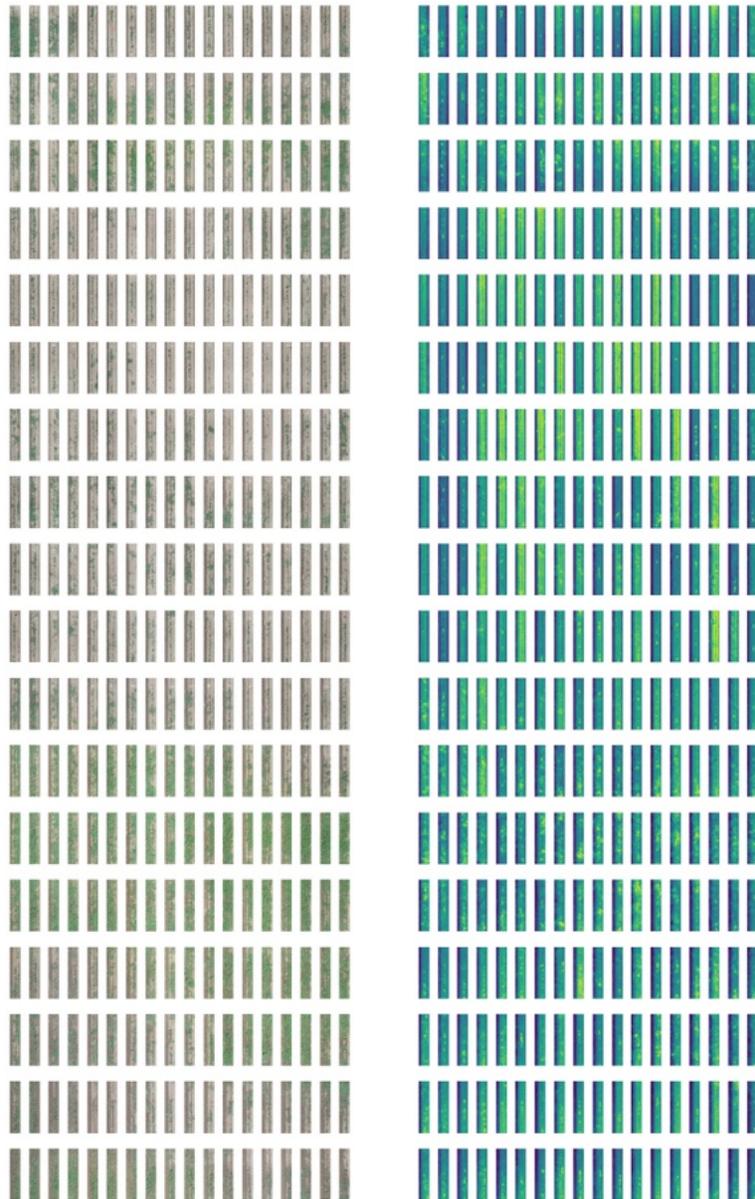


Figure 4: An example result of plot segmentation. Left: RGB, Right: Digital Elevation Model

2.4 Sorghum Plant Height Modeling

2.4.1 CIMIS Weather Data

Figure 5 shows weather data were collected to use the model input for Growing degree days in the height model of sorghum. Then growing degree days were calculated using $T_{base} = 8^{\circ}C$ and sampled in time for drone flight (Table 4).

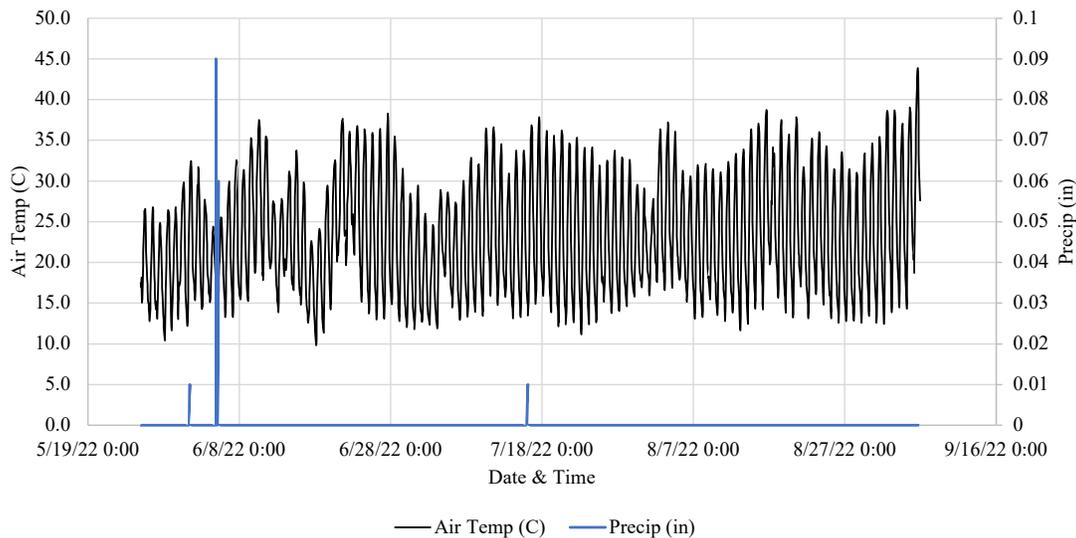


Figure 5: Weather data from CIMIS Station#6 (Sacramento Valley)

Table 4: Degree Days ($^{\circ}C$ -days) for Summer 2022

Fight #	Date Time	Degree Days
1	6/24/22 11:39 AM	0.00
2	7/1/22 10:23 AM	160.46
3	7/8/22 10:24 AM	303.34
4	7/15/22 10:20 AM	469.68
5	7/22/22 10:11 AM	639.77
6	7/29/22 11:14 AM	798.96
7	8/2/22 10:22 AM	888.40
8	8/5/22 10:23 AM	967.48
9	8/12/22 10:11 AM	1122.20
10	8/26/22 10:08 AM	1465.96
11	9/2/22 10:26 AM	1628.54

2.4.2 Empirical model for sorghum height

The height of the sorghum was empirically modeled using the acquired height data. At this time, the sigmoid function was used. In the final growth data, the height of sorghum was distributed in various ranges, as shown in Figure 6.

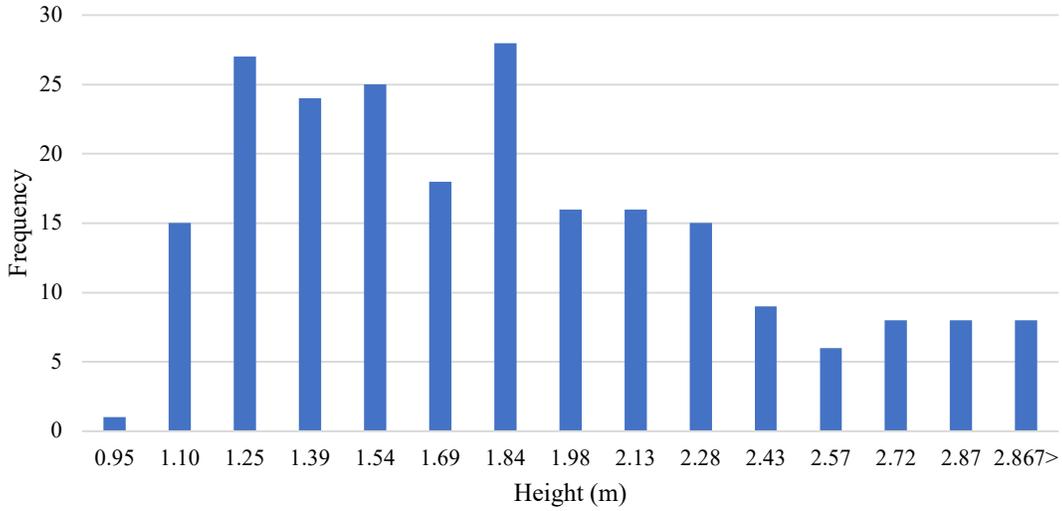


Figure 6: Histogram from 09/02 Sorghum height data

The cumulative probability distribution was calculated for the height data of the final image acquisition date to normalize the effect of various genotypes on the sorghum height, as shown in Figure 7. And plots corresponding to 0%, 25%, 50%, 75%, and 100% were selected. Furthermore, 11 sorghum height data were analyzed for the selected plot from June 24 to September 2, respectively.

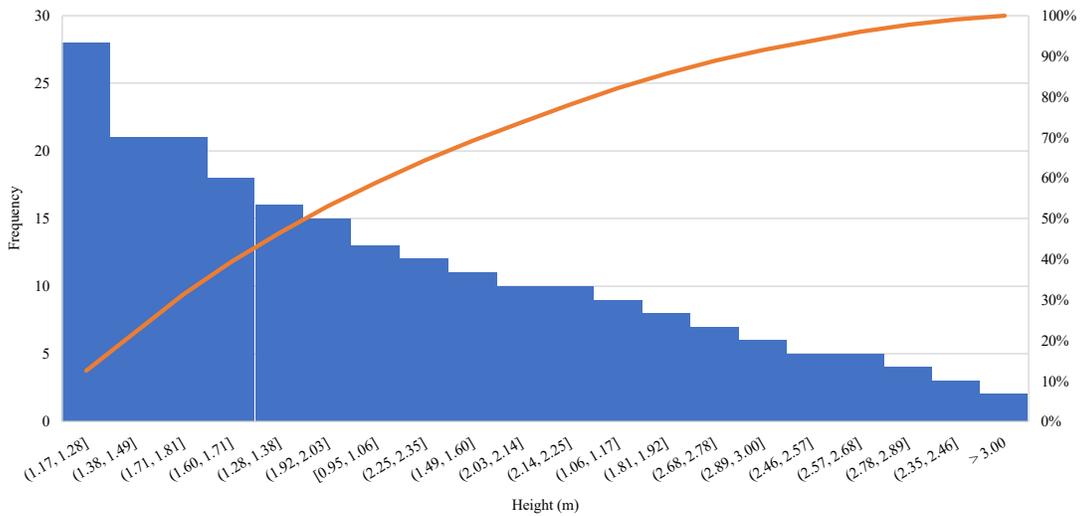


Figure 7: Cumulative Probability Histogram from 09/02 Sorghum height data

The height of the final growth step corresponds to y_{max} in the sigmoid function. In this case, it is assumed that y_{max} has a linear relationship with the value of the cumulative probability function (Eq. 1).

$$y_{max} = a * p + b, p = 0 \dots 1 \quad (1)$$

Table 5: Sorghum height of the selected 5 plot IDs

Date & Time	Degree Days($^{\circ}\text{C-days}$)	3107	3065	3012	3082	3055
6/24/22 11:39 AM	0.00	0.06	-0.12	0.00	-0.12	-0.15
7/1/22 10:23 AM	160.46	0.18	0.11	0.33	0.12	0.16
7/8/22 10:24 AM	303.34	0.15	0.39	0.52	0.39	0.36
7/15/22 10:20 AM	469.68	0.43	0.66	0.84	0.65	0.69
7/22/22 10:11 AM	639.77	0.66	0.78	1.12	1.12	1.12
7/29/22 11:14 AM	798.96	0.83	0.97	0.99	1.57	1.29
8/2/22 10:22 AM	888.40	1.05	2.06	1.74	2.19	3.12
8/5/22 10:23 AM	967.48	0.97	1.31	1.19	1.96	1.43
8/12/22 10:11 AM	1122.20	0.96	1.04	1.74	1.10	2.10
8/26/22 10:08 AM	1465.96	0.92	1.59	1.79	1.74	2.49
9/2/22 10:26 AM	1628.54	0.95	1.34	1.70	2.12	3.02
	Percentile	0%	25%	50%	75%	100%

According to the empirical formula, sorghum height can be modeled using Growing Degree Days (GDD) and Sigmoid functions[1] (Eq. 2).

$$y(GDD, p) = \frac{y_0 y_{max}}{y_0 + (y_{max} - y_0) \exp(-kGDD)} \quad (2)$$

The sorghum height model is optimized so that the R^2 (Eq. 3) of the modeled value \hat{y}_i and the observed value y_i is maximized.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

3 Results

3.1 Verification of Sorghum Height from Drone images

To verify the height data measured by the drone, the height of sorghum measured directly on the ground and the height measured by the drone were compared in the final growth stage. The ground measurement was done in October 2022. Figure 8 compares drone and ground measurements of sorghum height. As a result of the comparison, the R^2 value was calculated as 0.516. Since the sorghum height measured by the drone and measured on the ground are statistically significant, the height values will be used for further analysis.

3.2 Sorghum Height Model

Figure 9 shows the height data used for modeling and the results modeled with a sigmoid function. The height of Sorghum measured by drones showed some instability, with problems overshooting when the degree-days is 900. However, the sigmoid function was successfully modeled because it was fitted to maximize R^2 considering these noises. Table 6 shows the calculated model coefficients and its R^2 was 0.845.

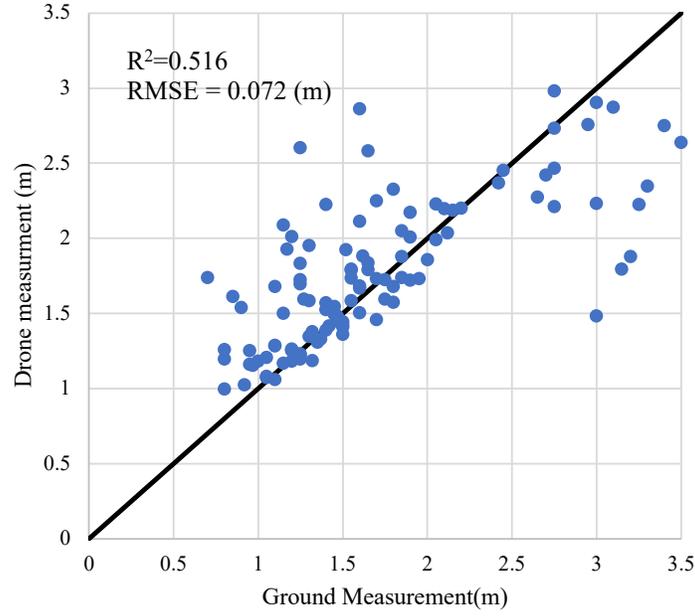


Figure 8: Comparison of ground measurement and drone measurement Sorghum height

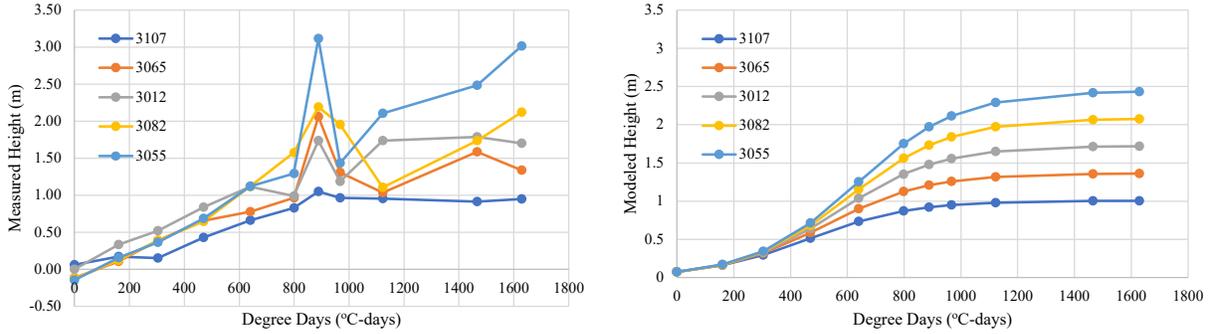


Figure 9: Sorghum height measured by drone (left) and modeled by sigmoid function (right)

Table 6: Model Coefficients for the Sorghum Height Model

	y_0	a	b	k	
	0.07	1.436729887	1.006527629	0.00551629	
p (plot_id)	0 (3107)	0.25 (3065)	0.5 (3012)	0.75 (3082)	1.0 (3055)
$y_{max} = a * p + b$	1.006527629	1.365710101	1.724892572	2.084075044	2.443257516
R^2	0.845323504	$RMSE(m)$	0.302884155		

Figure 10 shows that the height measured by the drone is set to the X axis, and the height measured from the ground is set to Y.

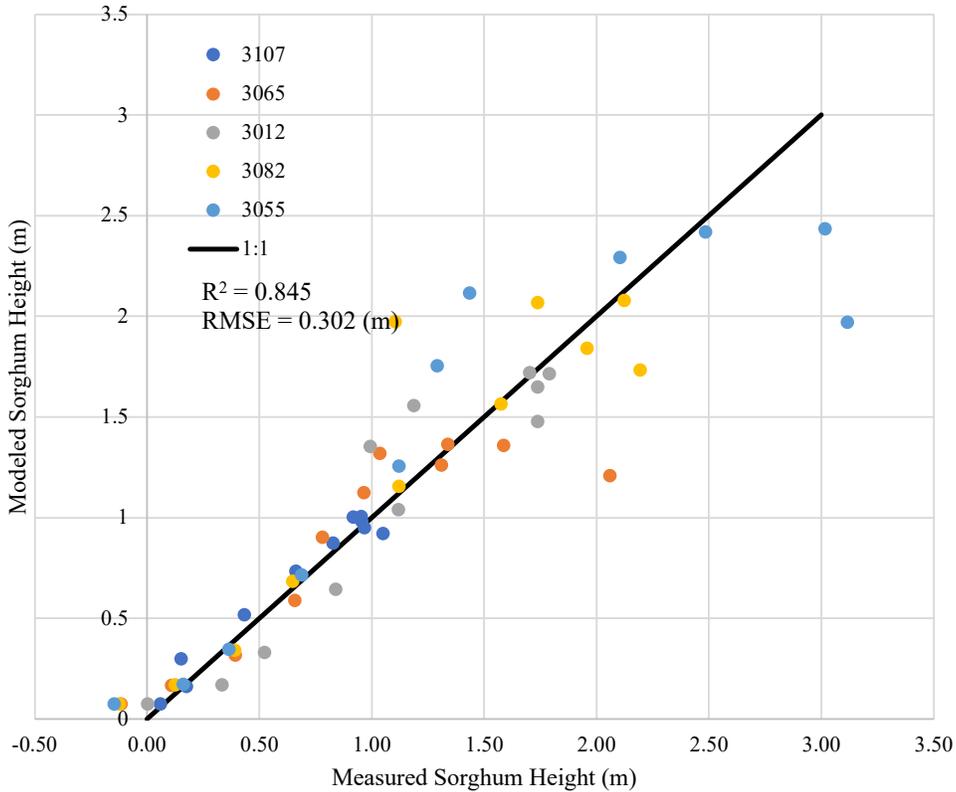


Figure 10: Comparison of modeled and drone measured Sorghum height

3.3 Validate Sorghum Height Model with Different Dataset

To verify the developed model, the developed model was validated with a different dataset [2]. The experiments were carried out on a field of sweet sorghum at the research farm of North Carolina A&T State University in Guilford County, North Carolina, in 2011. The research plots were situated at coordinates of longitude 36.06, latitude -79.73, and an elevation of 241.4 meters above sea level. The soil type was identified as Mecklenburg Sandy Clay Loam with a slope of 2 to 6 percent, moderately eroded and classified as fine, mixed, active, thermic Ultic Hapludal-fs. Based on the monthly average temperature presented in the paper, the Sine function (Eq. 4) for the average temperature was modeled using days after planting as a input variable, which was used to calculate the temperature and Growing Degree Days on the Sorghum height measurement day. Figure 11 and Table 7 show the temperature model and its coefficients.

$$T_{mean} = M * Sin(A * DAP + B) + C \quad (4)$$

The sorghum height measurement was performed seven times, and the height of the day when the Sorghum was planted was set to zeros. Table 8 shows the sorghum heights of the five plot IDs selected from the dataset. Similar to the model development stage, plots corresponding to the height of 0% to 100% percentile were selected in the final stage.

Table 7: Coefficients for the temperature model

M	a	b	C	RMSE	R2
12.63953879	0.014306464	19.59166354	13.6016104	0.733509719	0.99385974

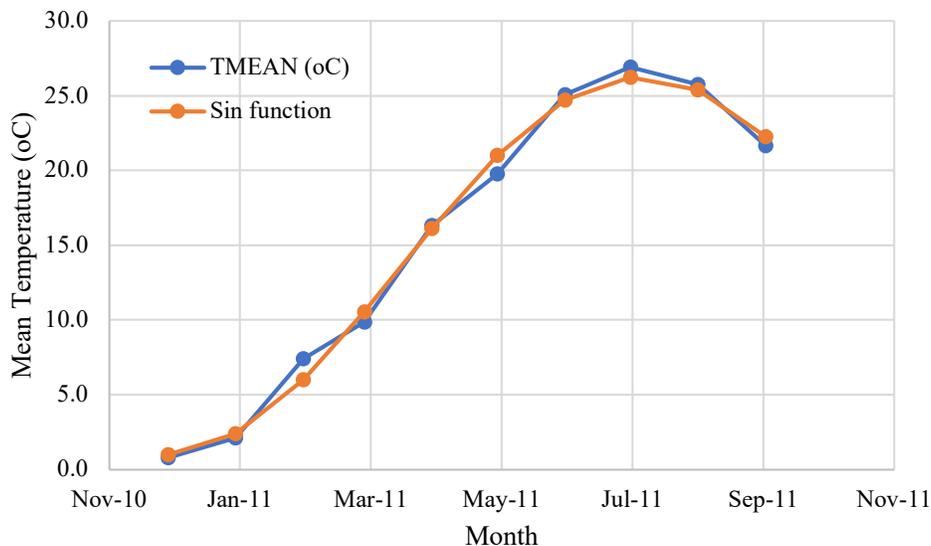


Figure 11: Weather data from the Validation Dataset

Table 8: Sorghum Height Measurement from the Validation Dataset

Date & Time	Degree Days ($^{\circ}\text{C}\text{-days}$)	R2V1T1	R3V1T2	R4V2T4	R2V2T4	R4V2T3
2011-05-23	0.0	0.0	0.0	0.0	0.0	0.0
2011-06-06	216.0	0.1	0.2	0.1	0.1	0.1
2011-06-20	448.0	0.2	0.4	0.3	0.5	0.4
2011-07-05	692.4	0.5	0.8	0.6	0.7	0.8
2011-07-18	944.7	0.5	1.1	1.1	1.2	1.3
2011-08-01	1203.0	0.7	1.9	1.3	1.5	1.8
2011-08-17	1466.0	0.5	2.1	1.9	2.2	2.0
2011-09-12	1657.8	1.8	2.7	3.0	3.2	3.8
Percentile		0%	25%	50%	75%	100%

Figure 12 shows the sorghum height from the validation dataset along the growing degree days and estimated sorghum height from the model. It can be seen that the developed model predicts lower heights values at the final growth stage.

Figure 13 shows a 1:1 plot between the actual height of the validation dataset and the model's predicted height data. Overall, the developed model is valid, showing $R^2 = 0.690$ and $RMSE = 0.546(\text{m})$. However, it can be seen that the model we developed predicts higher values at the early stage while lower values at the end of growth. In particular, the model we developed predicted the maximum height of Sorghum up to 2.5 meters, which differed from the actual measurement result rising up to 3.8 meters.

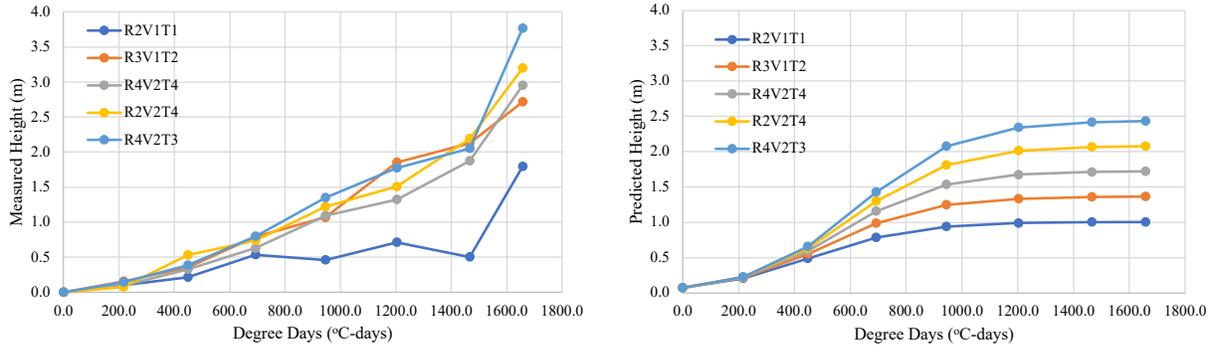


Figure 12: Sorghum height from validation dataset (left) and estimated by sigmoid function using growing degree days (right)

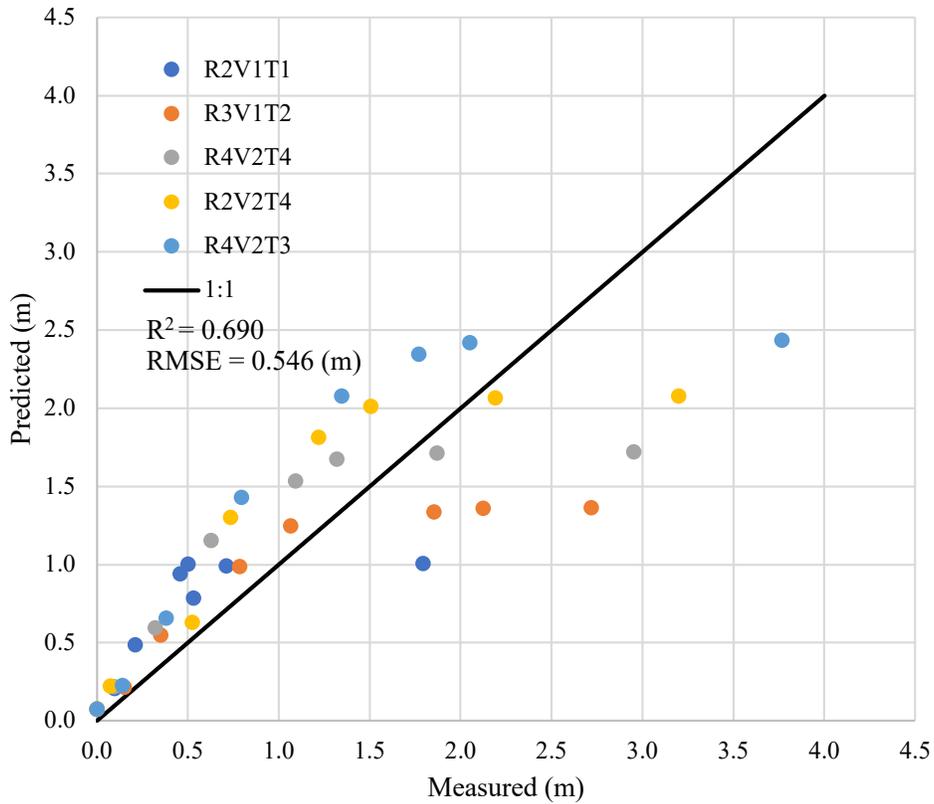


Figure 13: Comparison of estimated and measured Sorghum height from the validation dataset

4 Discussion

4.1 Accuracy of drone height measurements

It was found that the drone measured higher height for the low sorghum height and the drone measured lower height for the high sorghum height values. Unstable height measurements can explain it due to noise on the 3D surface measured by drones. If the height of the crop is low, the noise can make the height may have been measured higher. On the other hand, if the height of the crop is tall, the structure of a slender sorghum that humans can measure may have been difficult to capture in drones. Therefore, in future studies, it is necessary to verify the height measured by drones once again and improve performance to measure the height of crops accurately.

4.2 Applying the Model to Senegal Climate Data

Sorghum is one of the important crops that can withstand the harsh environment of Africa. Therefore, we looked at how the selected cultivars used in the developed model will grow by applying the developed model to the climate of Senegal. Figure 14 shows Senegal's lowest annual maximum temperature obtained by World Meteorological Organization [4].

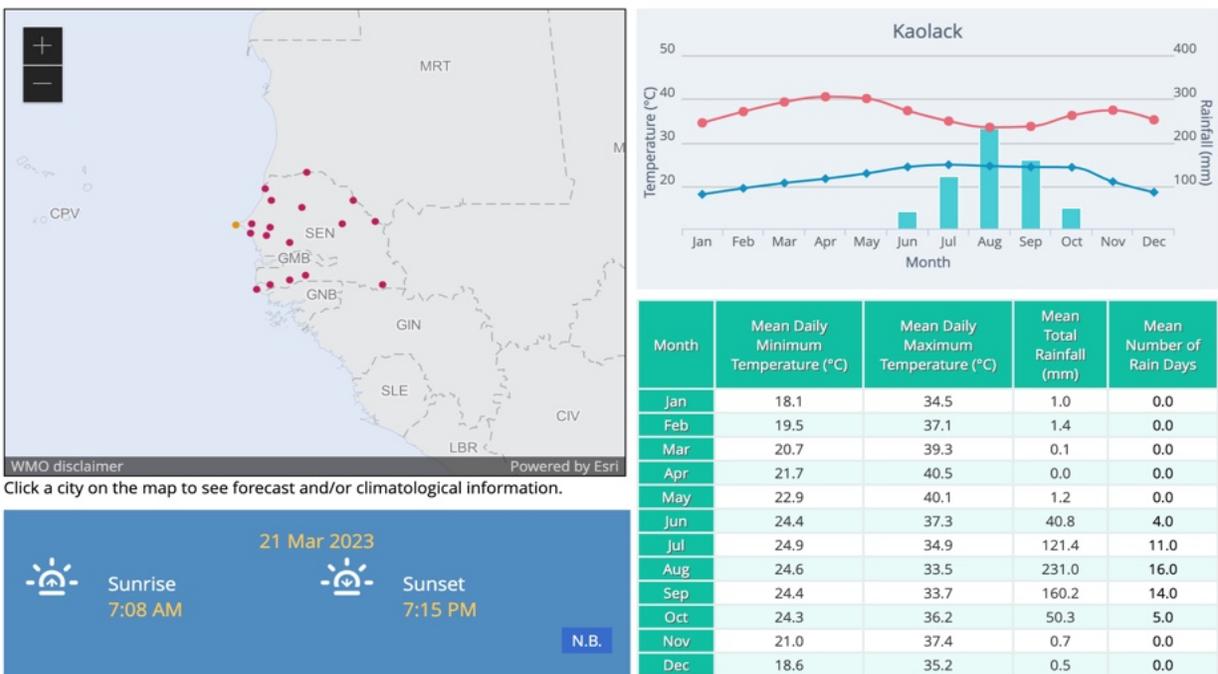


Figure 14: Year-round climate graph for the Senegal Kaolack region

According to the USDA International Production Assessment Division, Sorghum in the Senegal region begins cultivation in mid-June and harvests after September [3]. Therefore, Growing Degree Days were calculated using the average value of the minimum and maximum temperatures from June 15 to November 15. Figure 15 shows the predicted Sorghum height values of the selected cultivars.

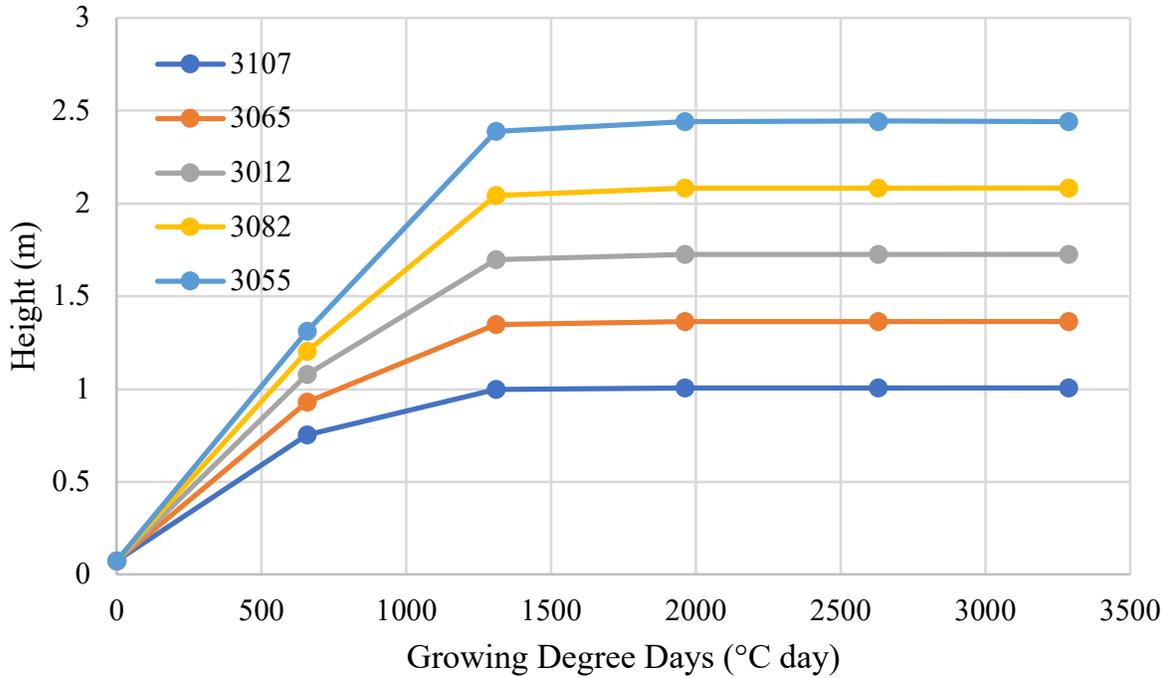


Figure 15: Predicted Sorghum height values of the selected cultivars

In the climate of the Senegal region, it can be predicted that Sorghum will grow close to its maximum height within two months. When harvesting begins a month after reaching its full height, the estimated harvest time is September 15, which is consistent with the usual Sorghum harvest time in Senegal as shown in Figure 16[3].



Figure 16: West Africa Sorghum Calendar

References

- [1] Brian Bailey. Plant and crop systems modeling. 2023.
- [2] Ashwin Kumar Devudigari. Sweet sorghum production based on fertilizer rates, varieties and use of grain sorghum model. 2011.
- [3] USDA IPAD. Senegal sorghum area, yield and production. retrieved march 22, 2023, from <https://ipad.fas.usda.gov/countrysummary/default.aspx?id=sg&crop=sorghum>.
- [4] World Meteorological Organization. World weather information service. retrieved march 22, 2023, from <http://worldweather.wmo.int/en/city.html?cityid=2920>.