

# Part V

## Appendices



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# Wageningen 3D Data

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This appendix covers the visualisations of raw point clouds and key processing steps of the data of the Wageningen University & Research (WUR) experiment covered Chapter 9.

Section A.1, Potatoes, shows the raw point clouds of both light detection and ranging sensors (lidars), as well as the merged strip with borders used for the slice calculations, in Figures A.1 through A.12. The slice volumes are extracted from the point clouds seen here, and their distribution is visualised in Figure 9.4 on page 113.

Section A.2, Cabbages, is split up into two sections. Section A.2.1 shows the merged clouds, the weighted sums of the central two rows, and the cluster volumes based on Euclidean distance, in Figures A.13 through A.24. The volumes seen here produce the boxplot shown in Figure 9.12 on page 119. This is followed by Section A.2.2 showing the  $J_s$  curves of each measurement and their automatically calculated cut-off values in Figure A.25. These curves illustrate the distribution of  $J$  values in each of the clouds, and the cut-off values shown here extract the vegetation (high values of  $J$ ) from the overall clouds. Visually, this can be linked to the images shown in Section A.2.1 as the step between subfigures (b) and (c), before the vegetation is clustered and their volumes calculated.

## A.1 Potatoes

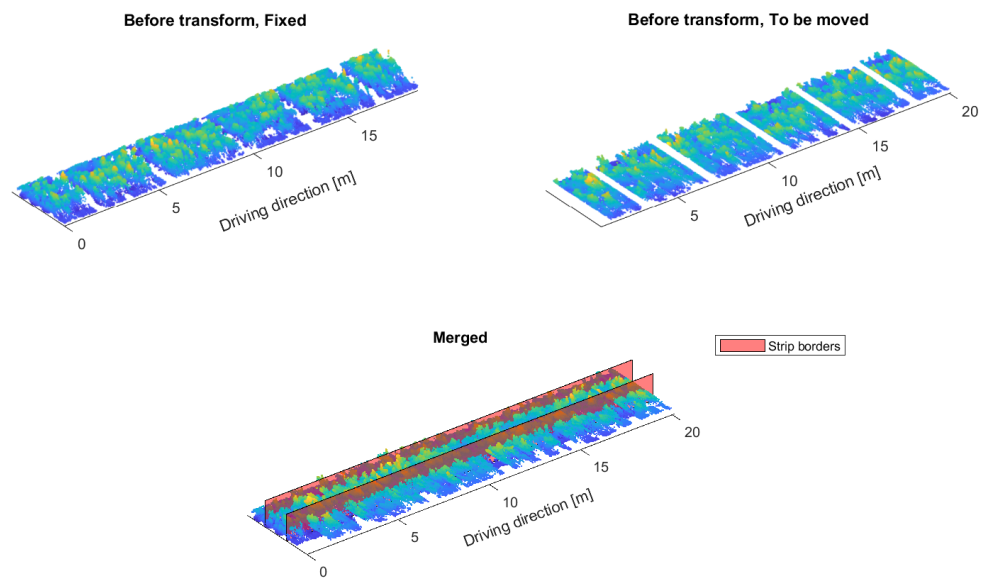


Figure A.1 Potato measurement 1: strip.

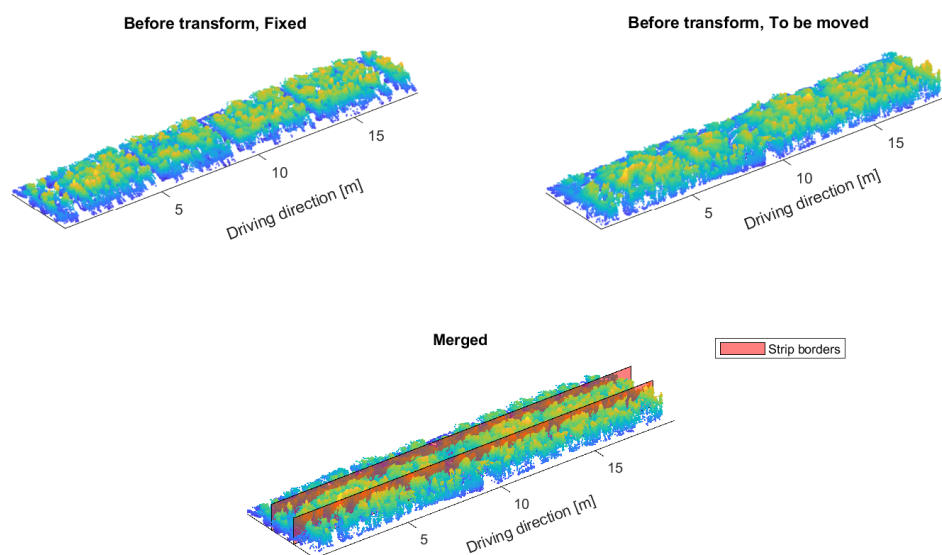


Figure A.2 Potato measurement 2: strip.

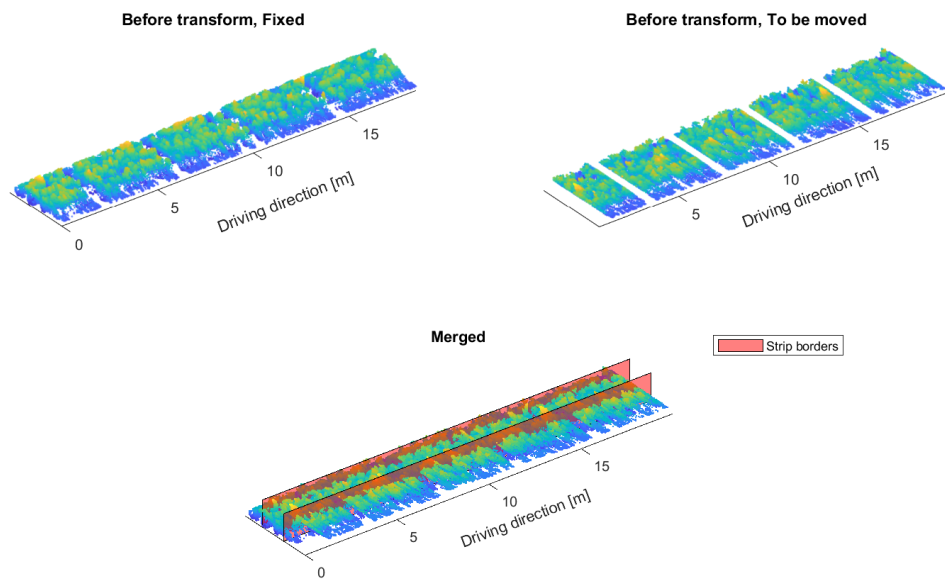


Figure A.3 Potato measurement 3: strip.

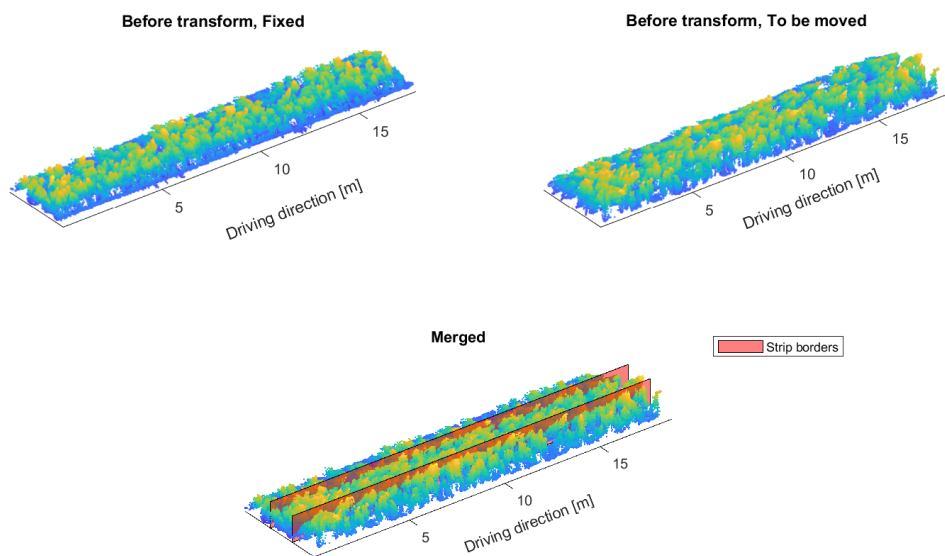


Figure A.4 Potato measurement 4: strip.

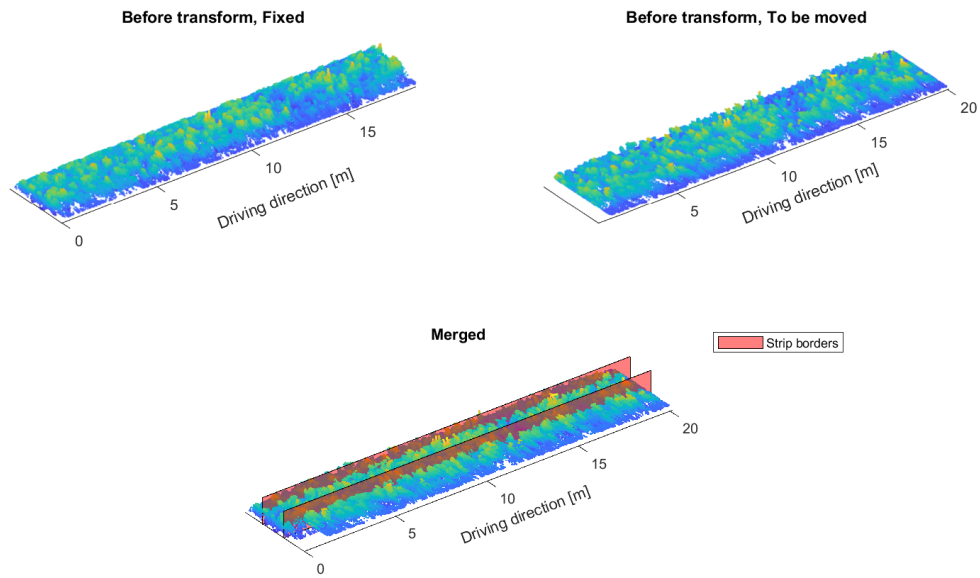


Figure A.5 Potato measurement 5: strip.

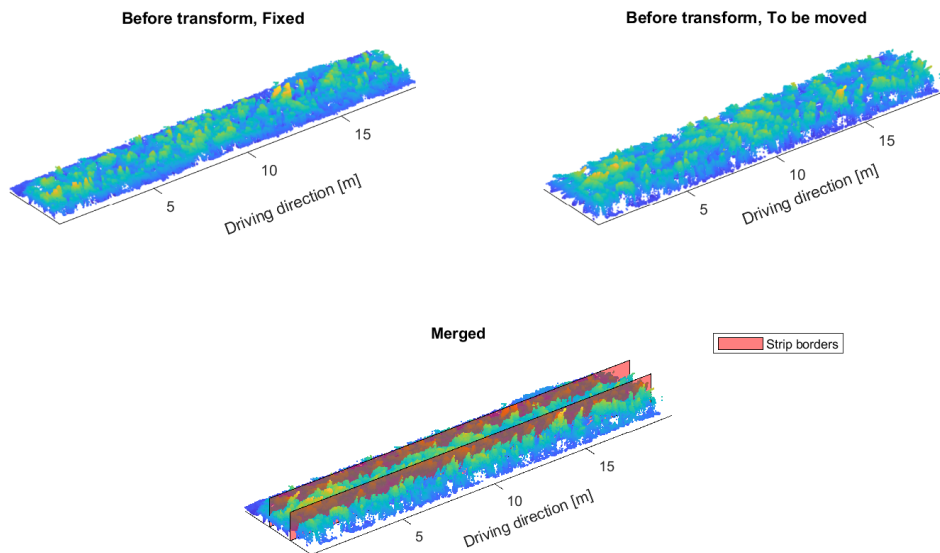


Figure A.6 Potato measurement 6: strip.

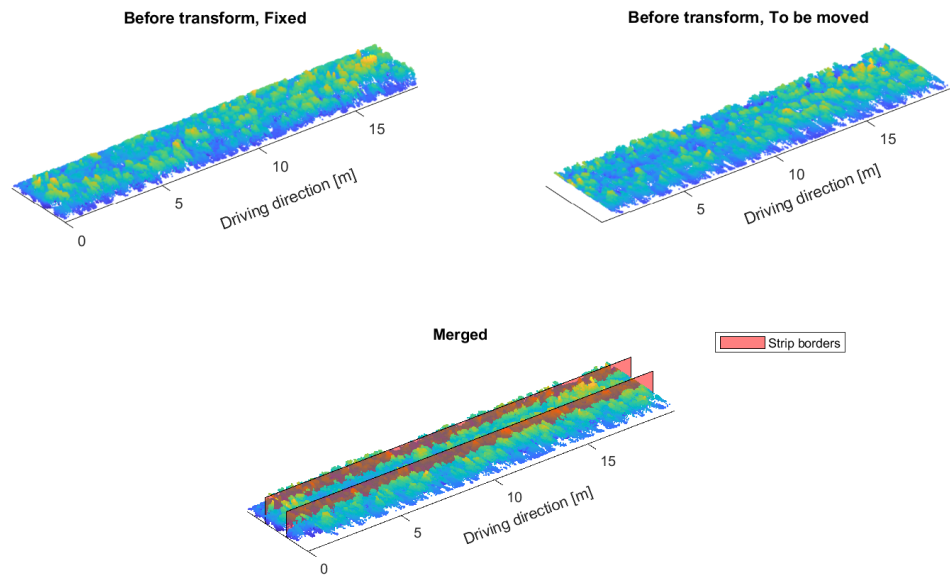


Figure A.7 Potato measurement 7: reference strip.

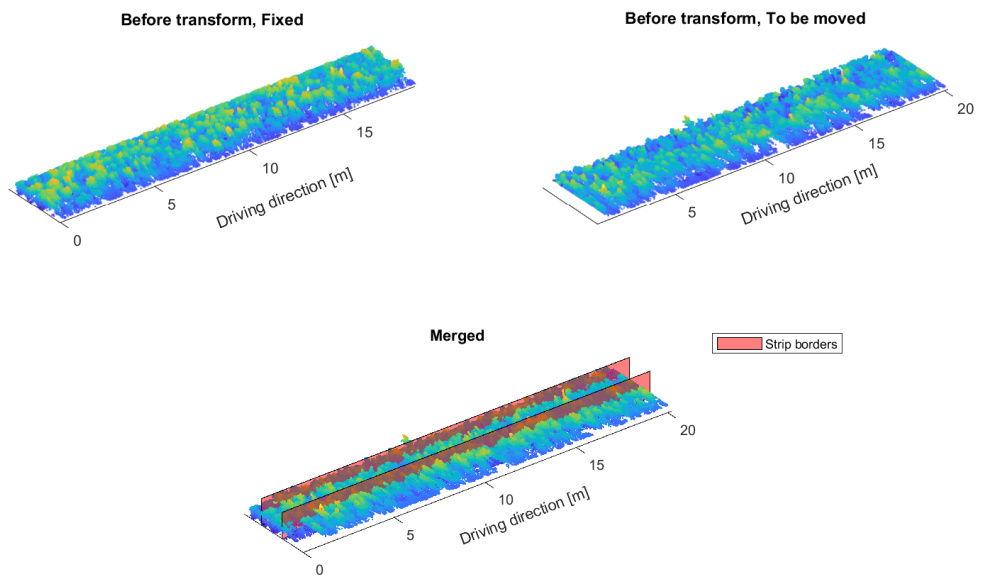


Figure A.8 Potato measurement 8: reference strip.

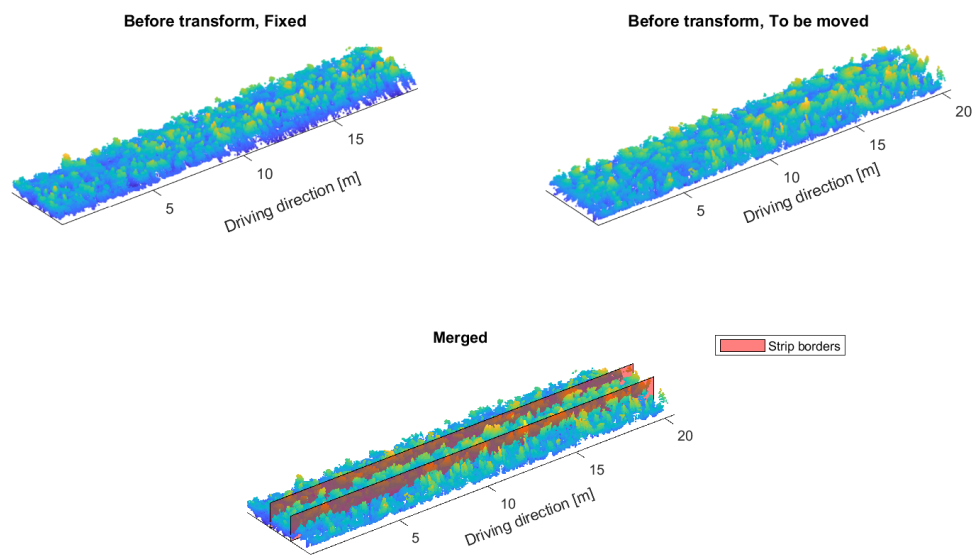


Figure A.9 Potato measurement 9: monoculture field.

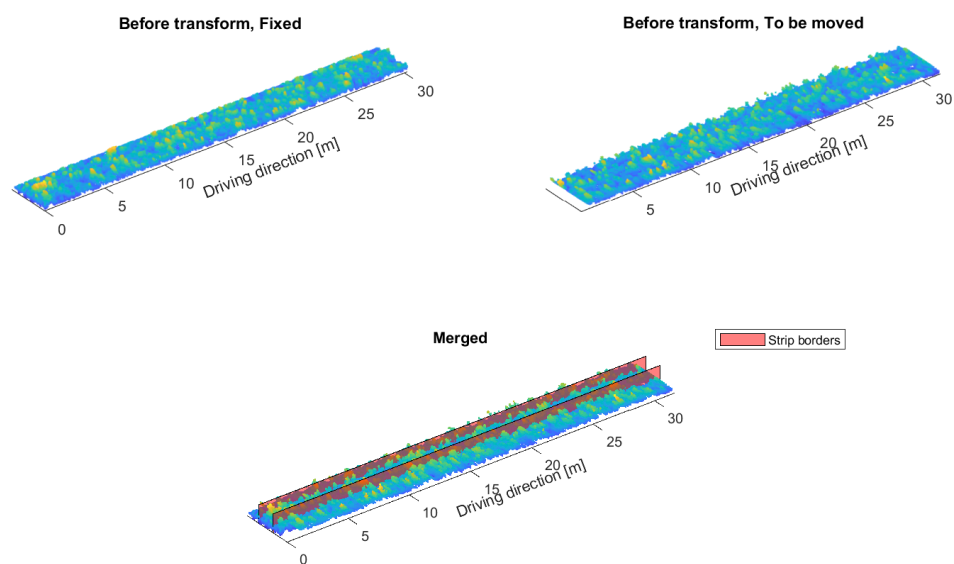


Figure A.10 Potato measurement 10: monoculture field.

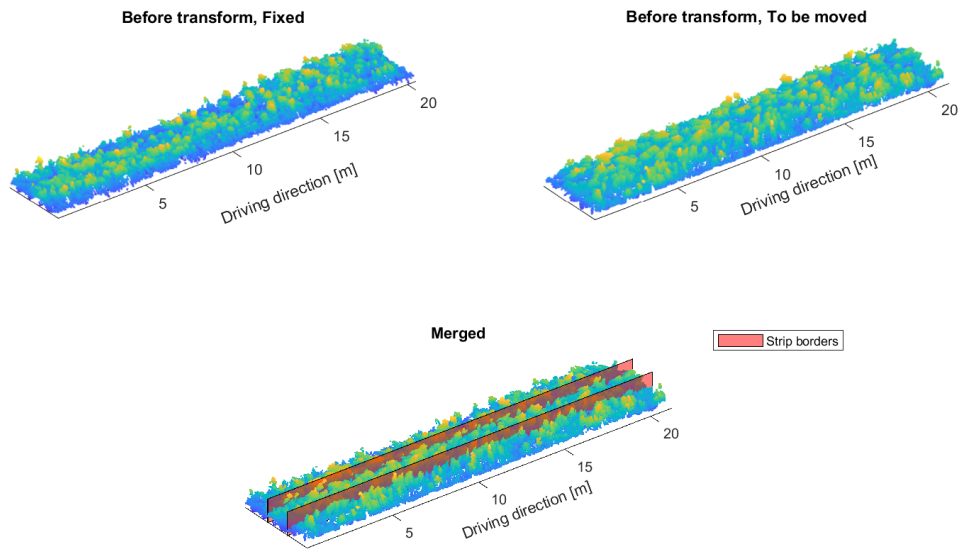


Figure A.11 Potato measurement 11: monoculture field.

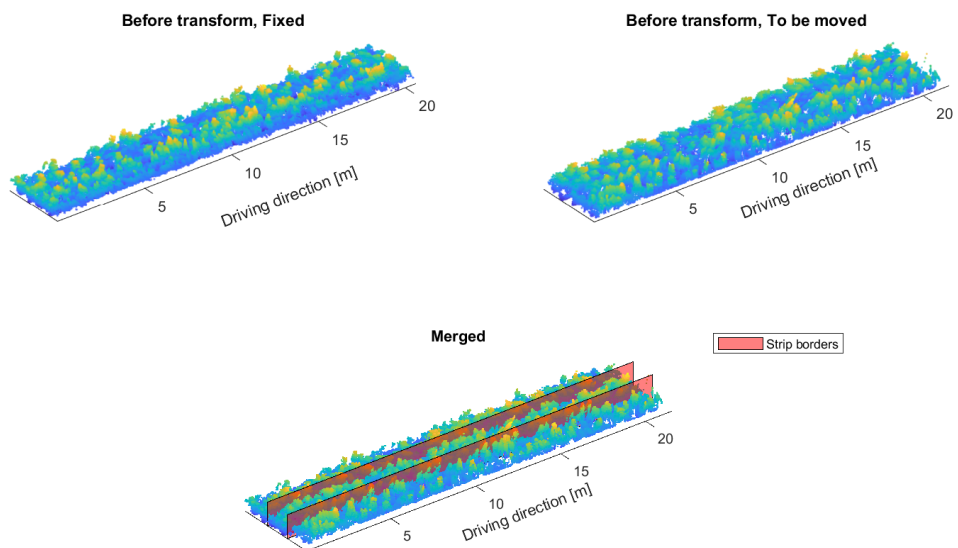
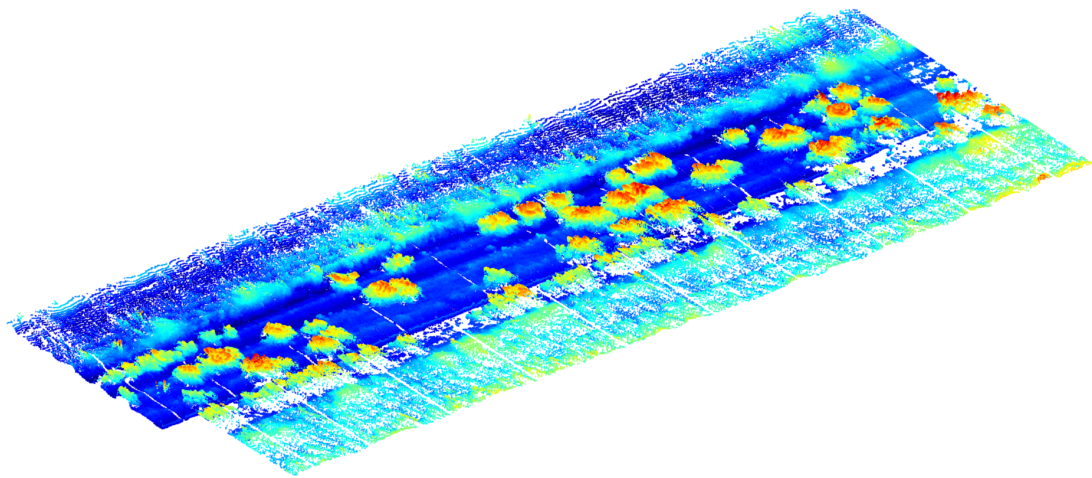


Figure A.12 Potato measurement 12: monoculture field.

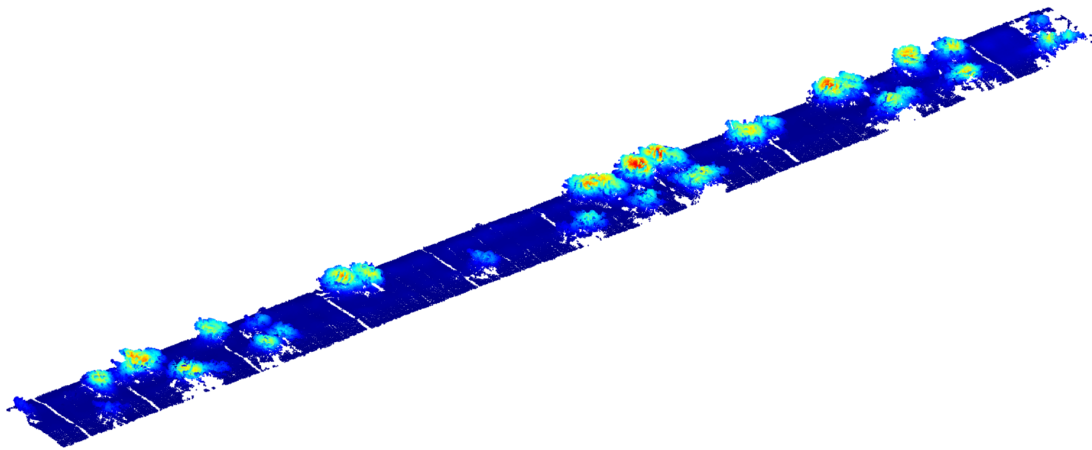
## A.2 Cabbages

### A.2.1 Merged Clouds

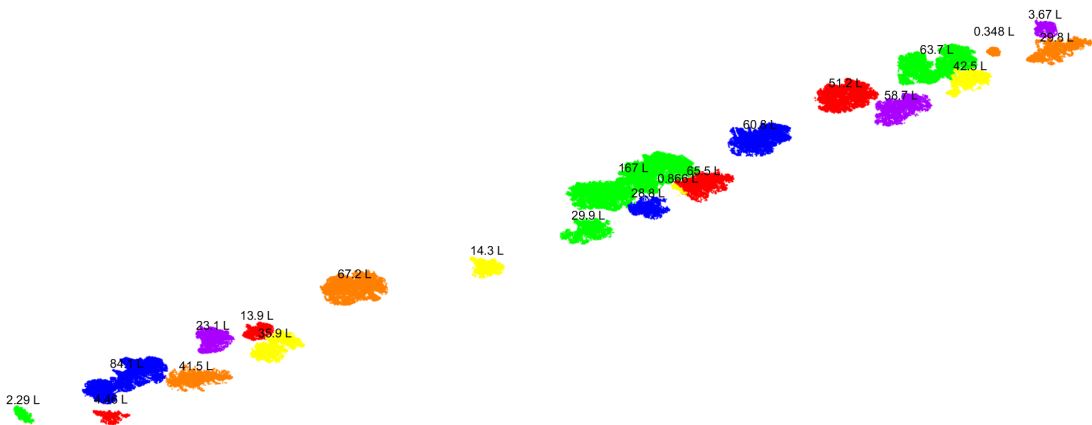
In this section, each image contains the merged point clouds of both lidars coloured by height in (a), followed in (b) by the excerpt of the central two rows for which the weighted sum  $J$  was calculated. Based on the cut-off graphs shown in the following section the distinction between soil and vegetation was made, after which the vegetation was clustered based on Euclidean distance: all plants that did not touch each other were separated in this manner. All clusters were then converted into volumes, the size of which is printed on top of each of the clusters in (c). Every image covers a single measurement.



(a)

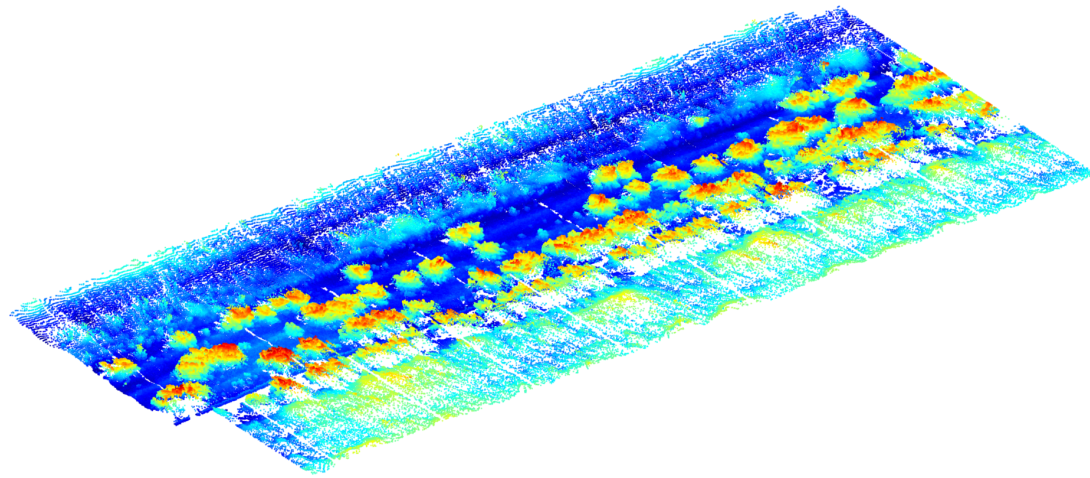


(b)

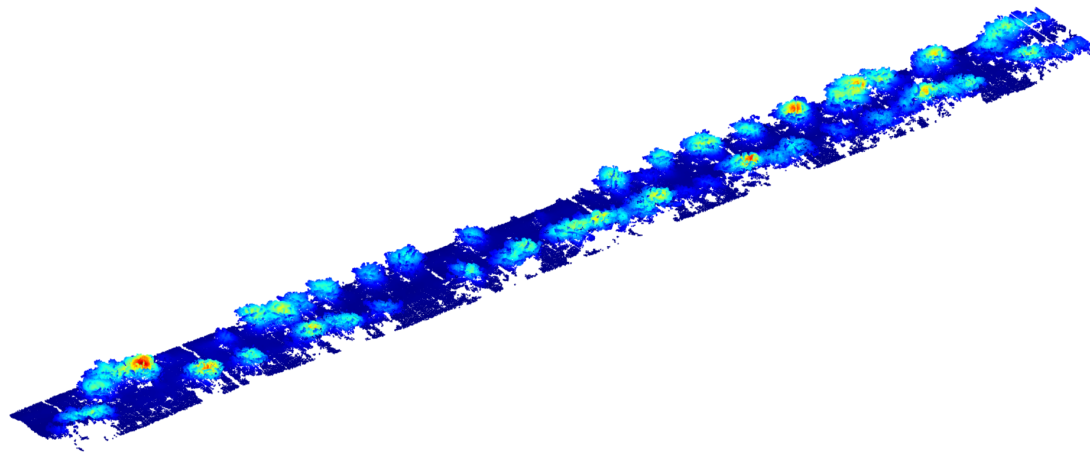


(c)

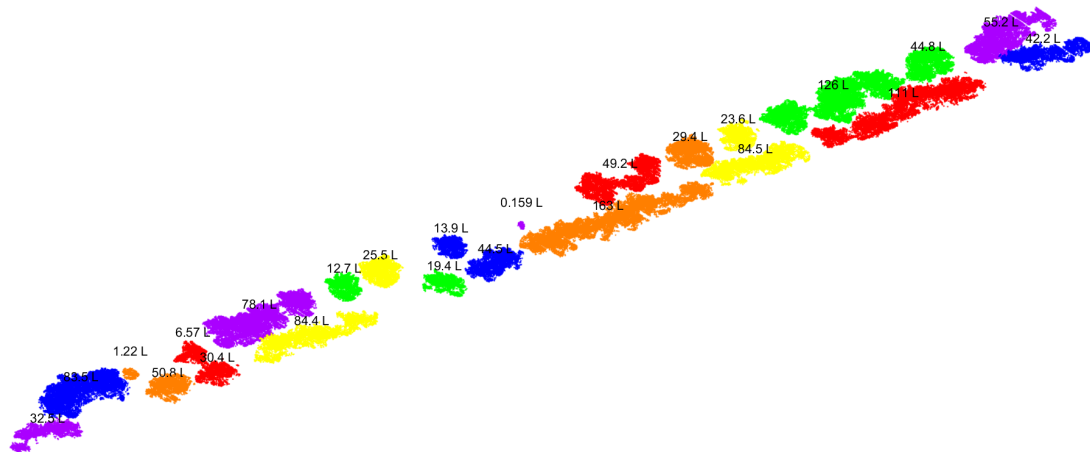
**Figure A.13** Cabbage measurement 1: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

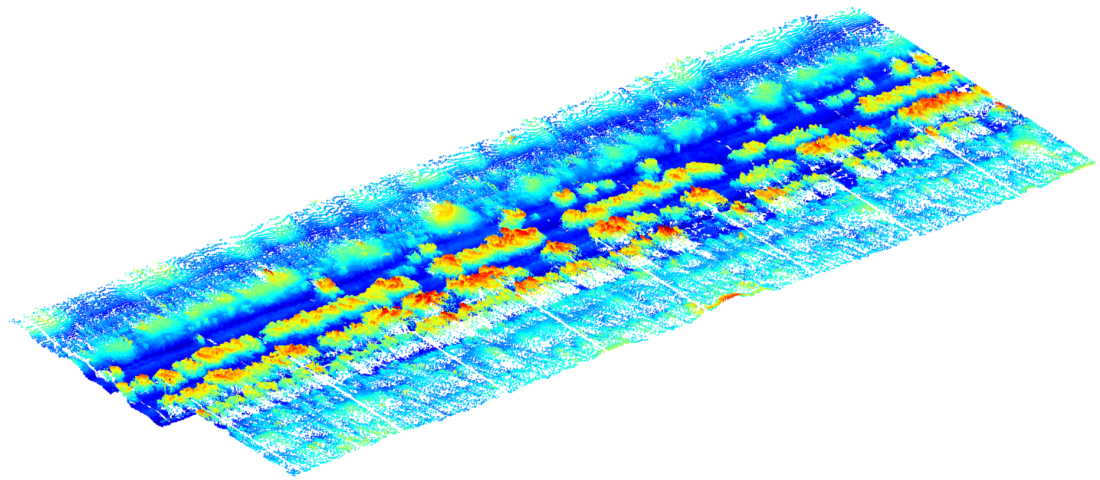


(b)

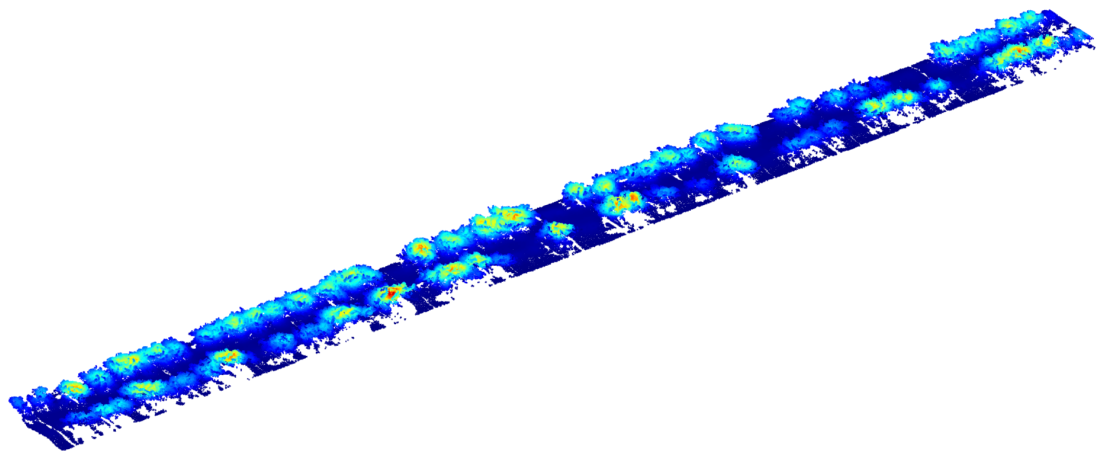


(c)

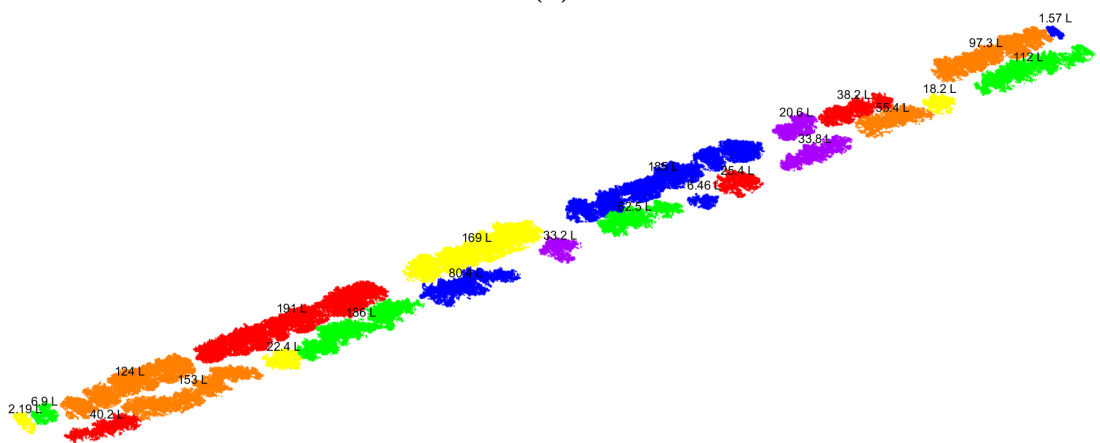
**Figure A.14** Cabbage measurement 2: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

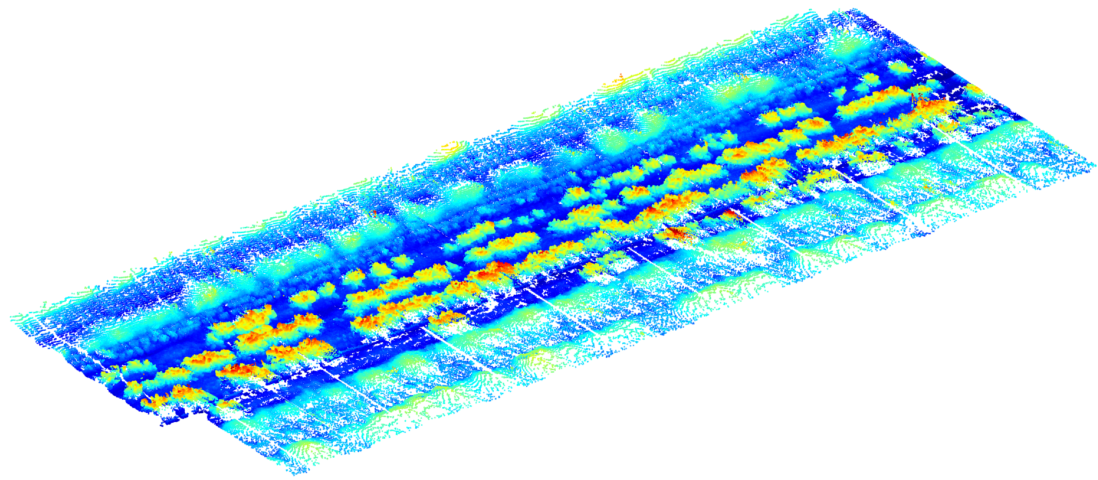


(b)

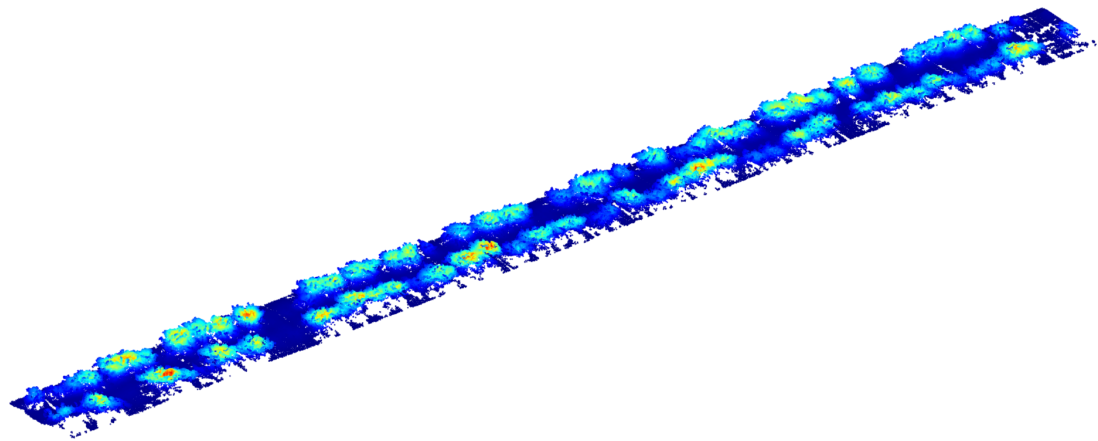


(c)

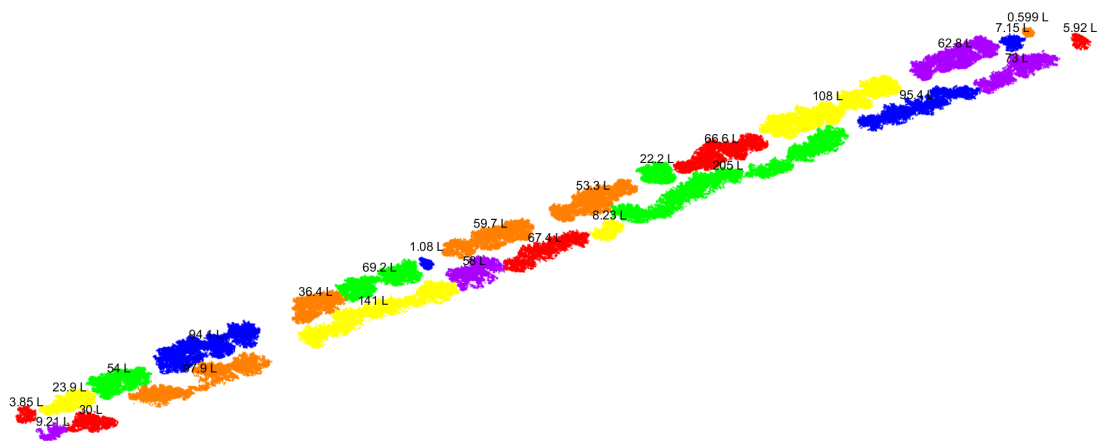
**Figure A.15** Cabbage measurement 3: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

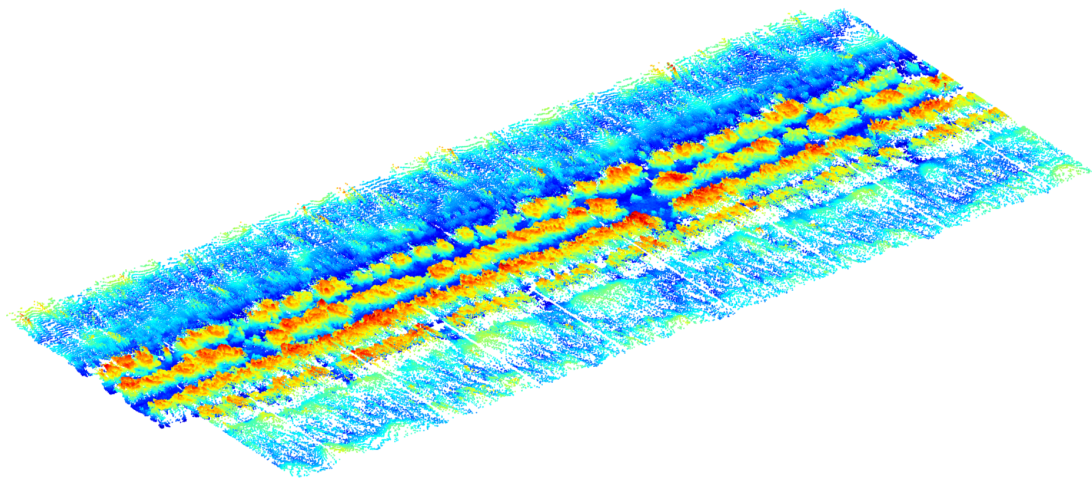


(b)

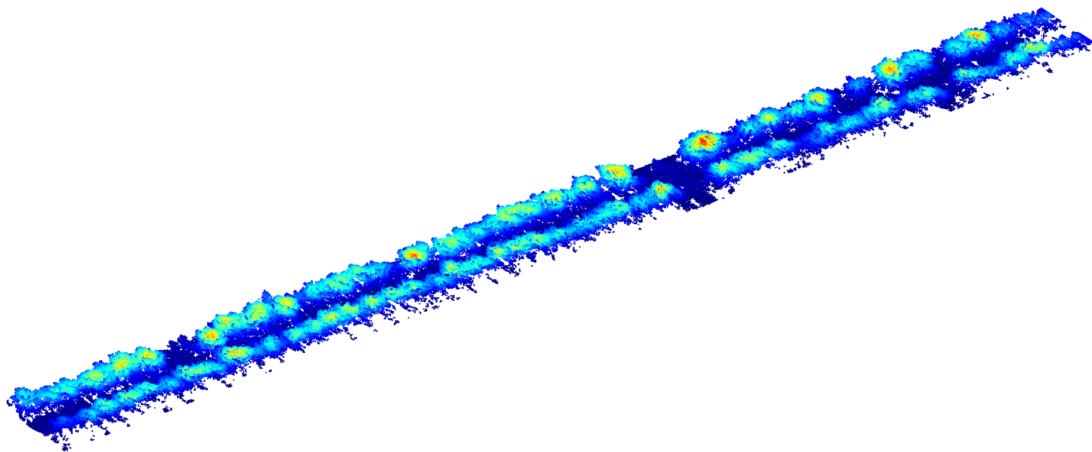


(c)

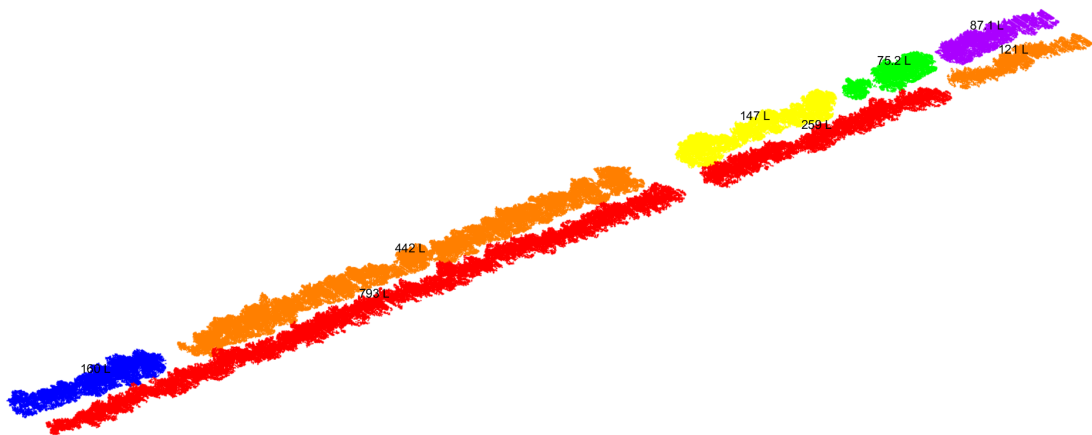
**Figure A.16** Cabbage measurement 4: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

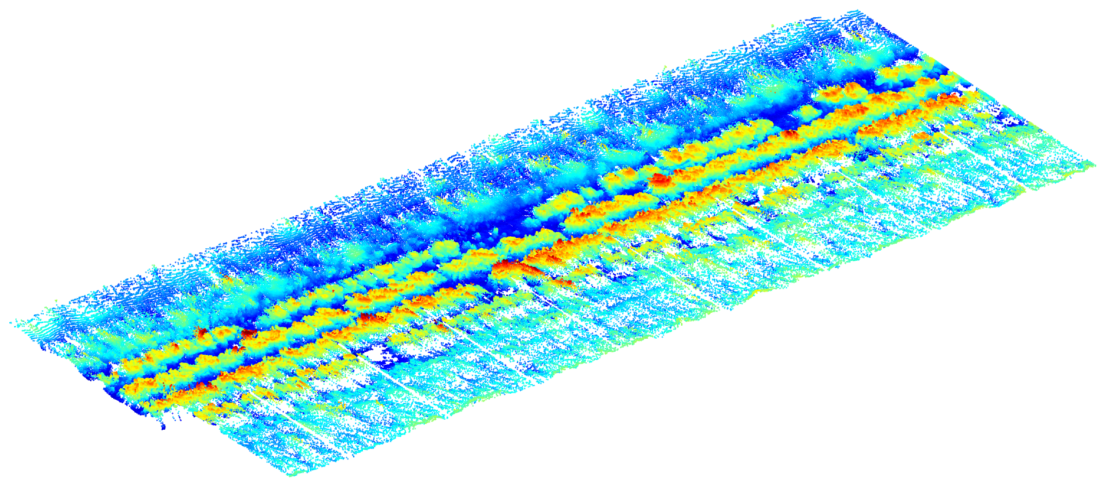


(b)

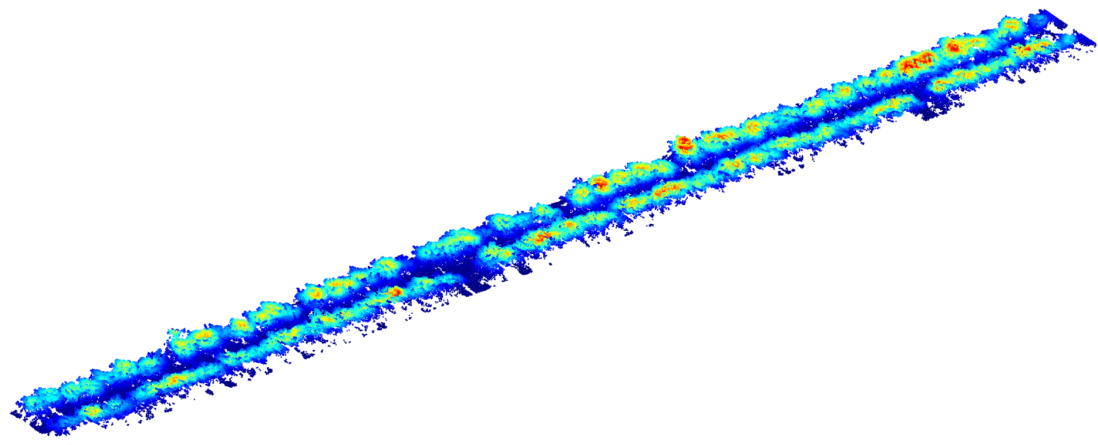


(c)

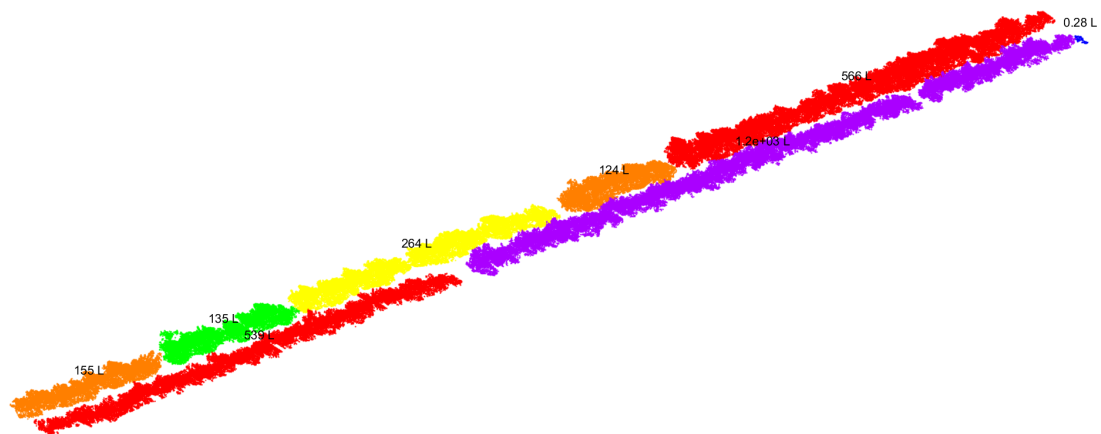
**Figure A.17** Cabbage measurement 5: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

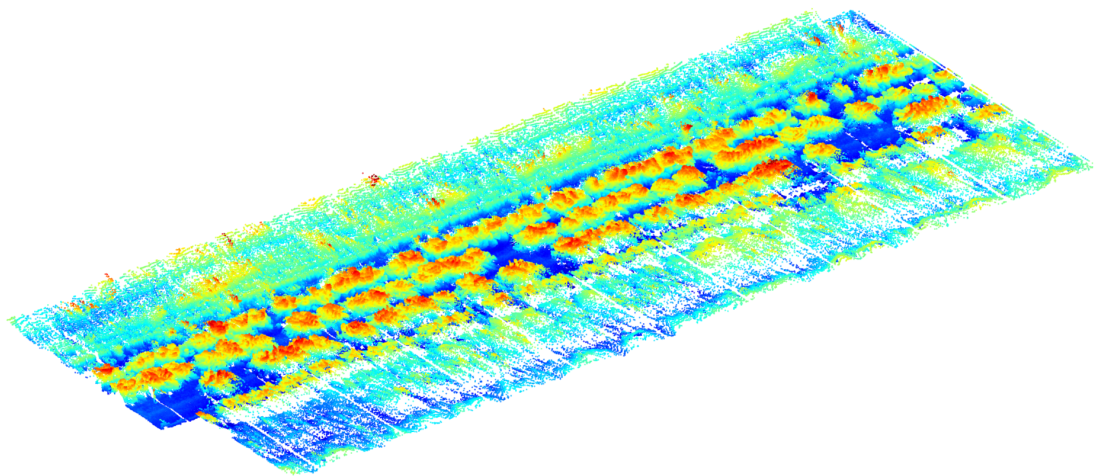


(b)

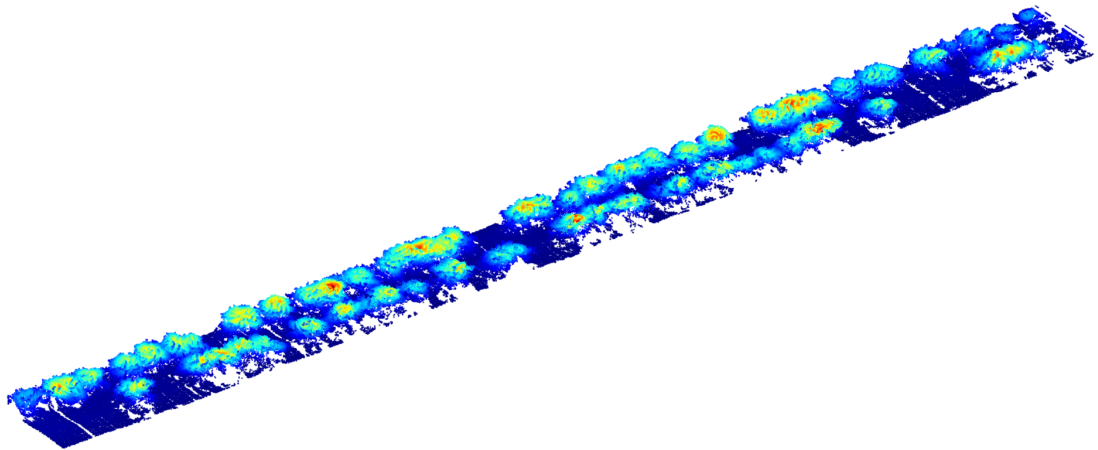


(c)

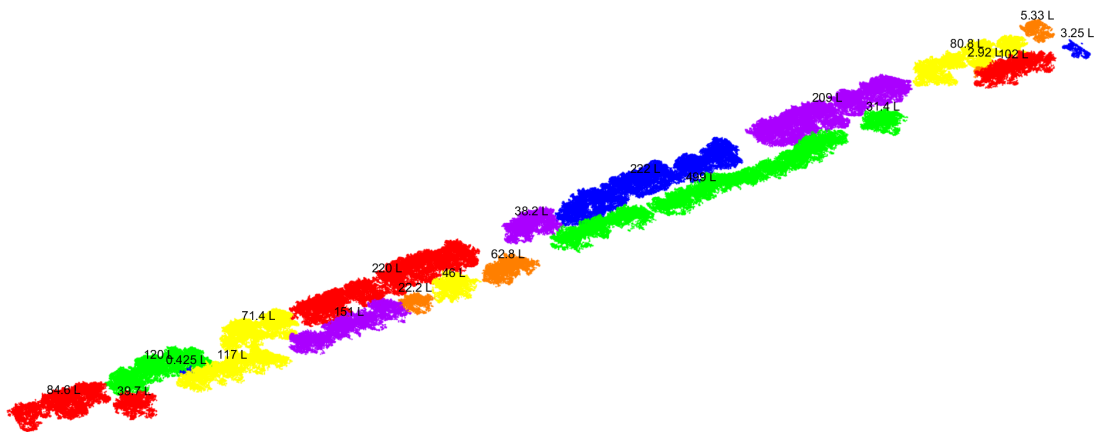
**Figure A.18** Cabbage measurement 6: strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

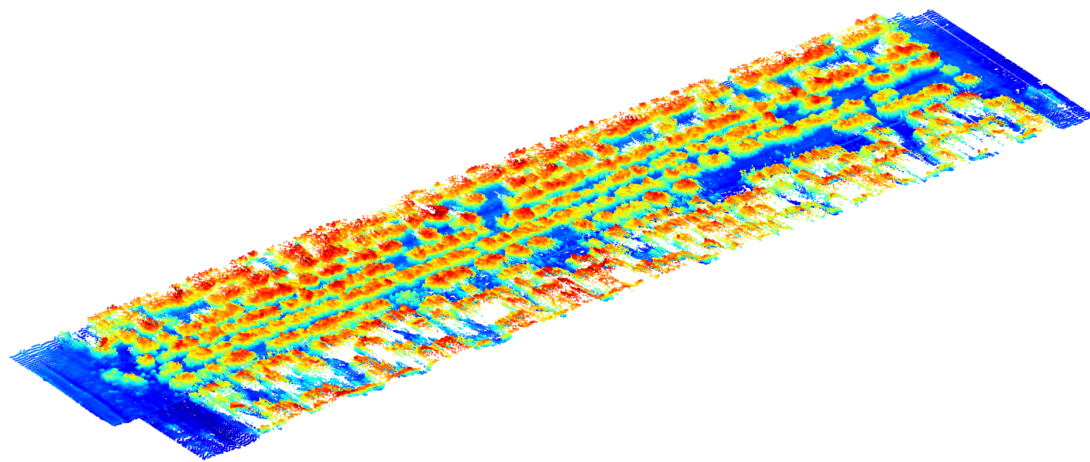


(b)

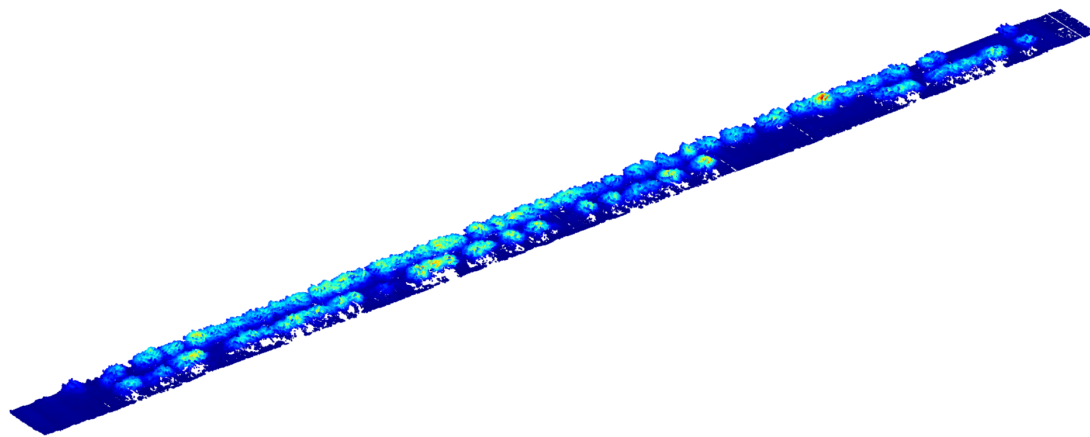


(c)

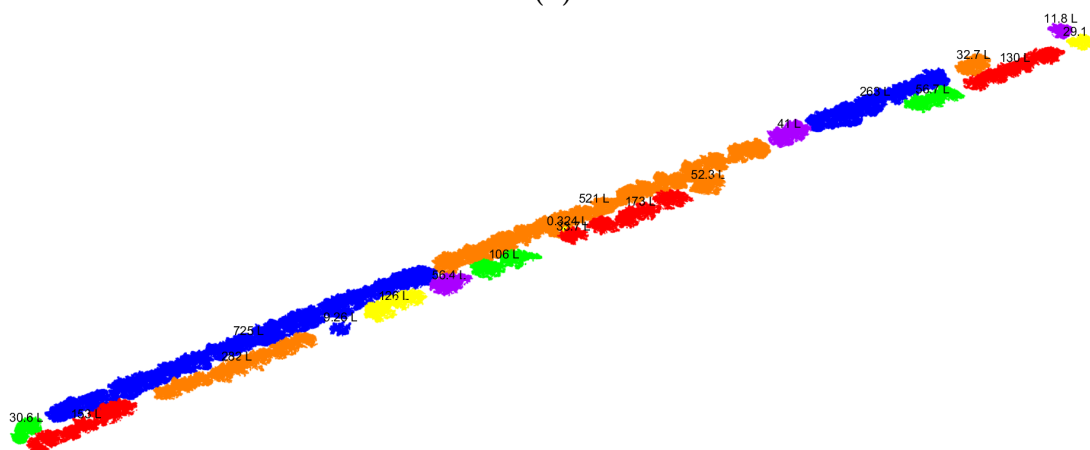
**Figure A.19** Cabbage measurement 7: reference strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

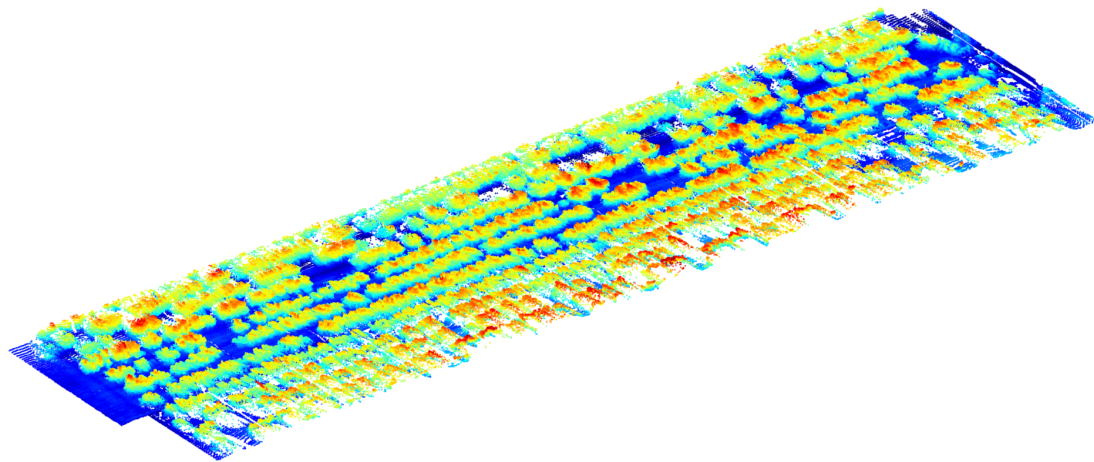


(b)

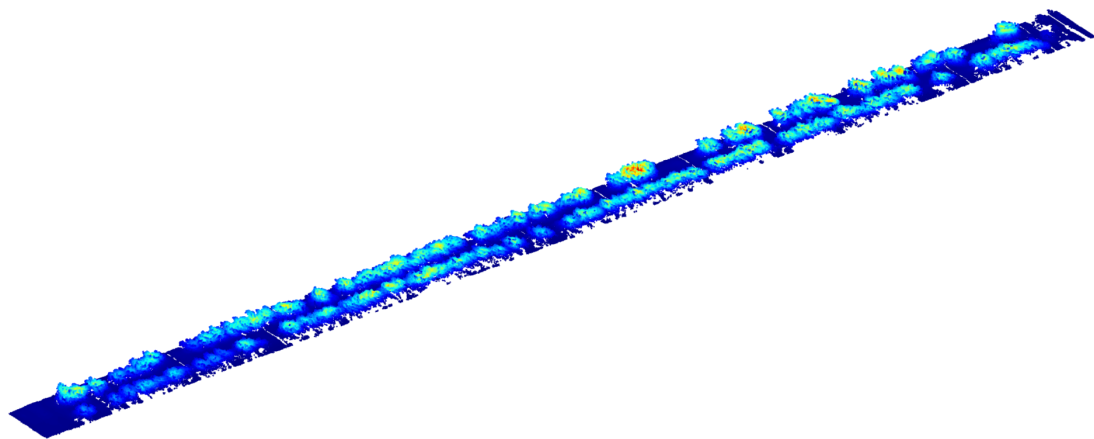


(c)

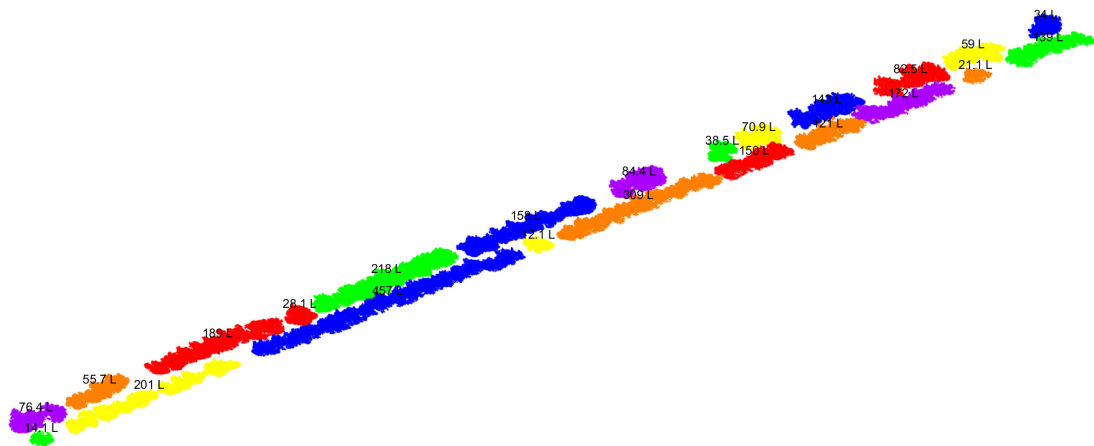
**Figure A.20** Cabbage measurement 8: monoculture. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

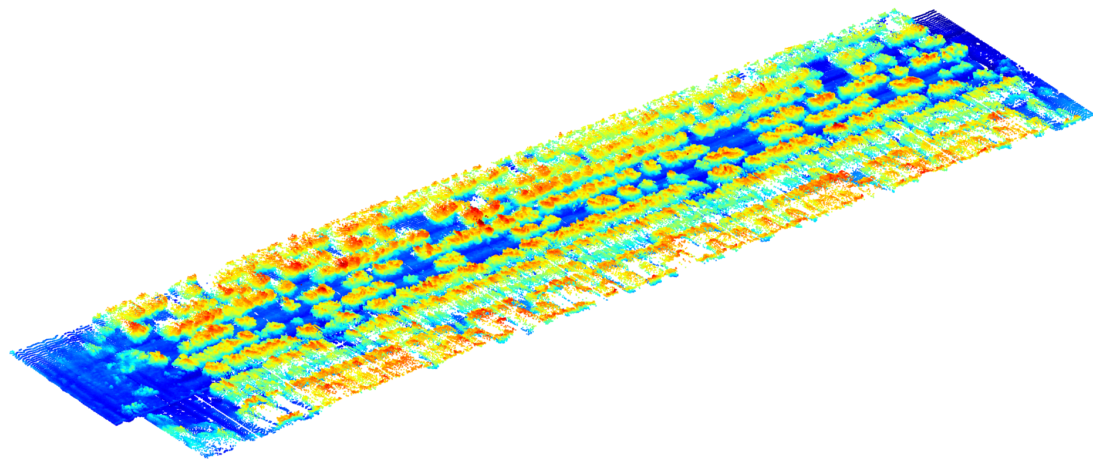


(b)

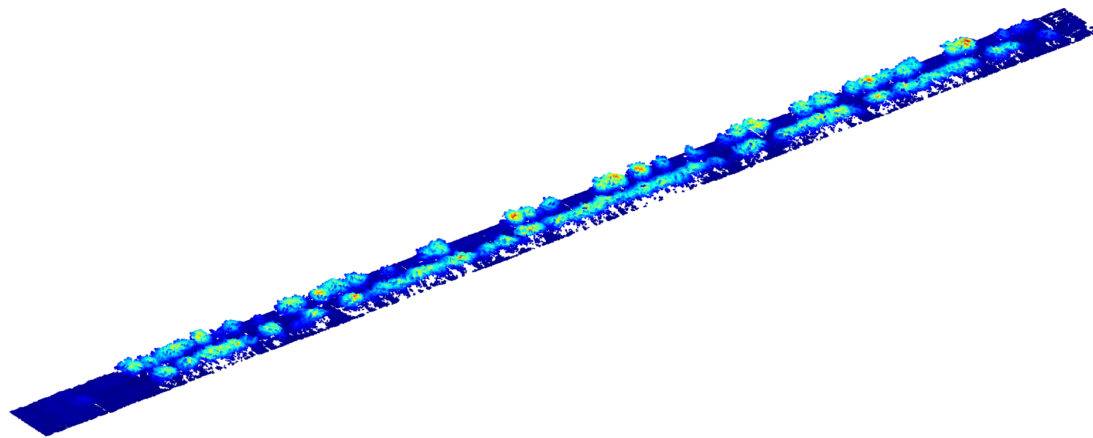


(c)

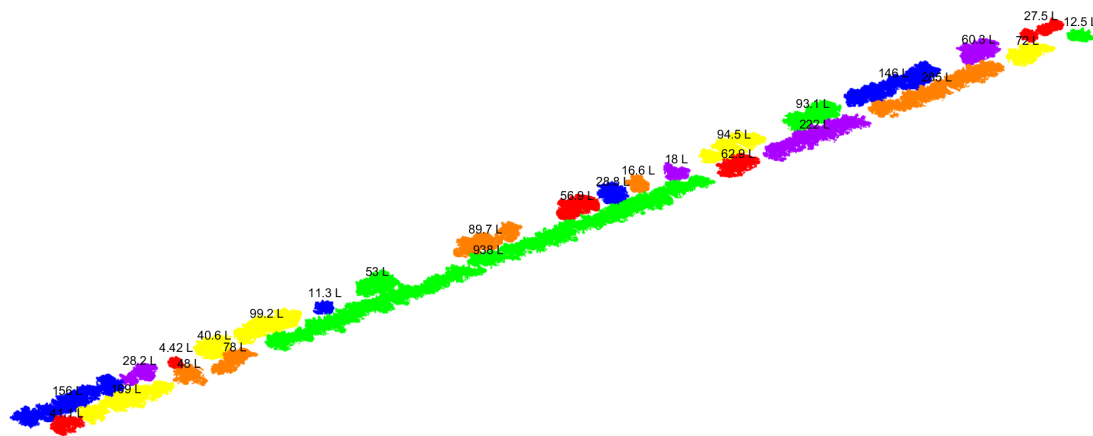
**Figure A.21** Cabbage measurement 9: monoculture. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

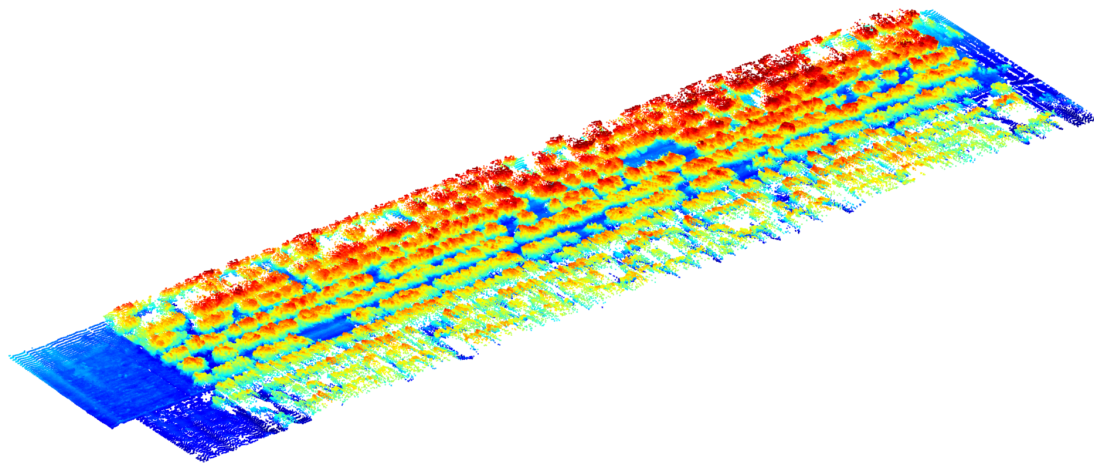


(b)

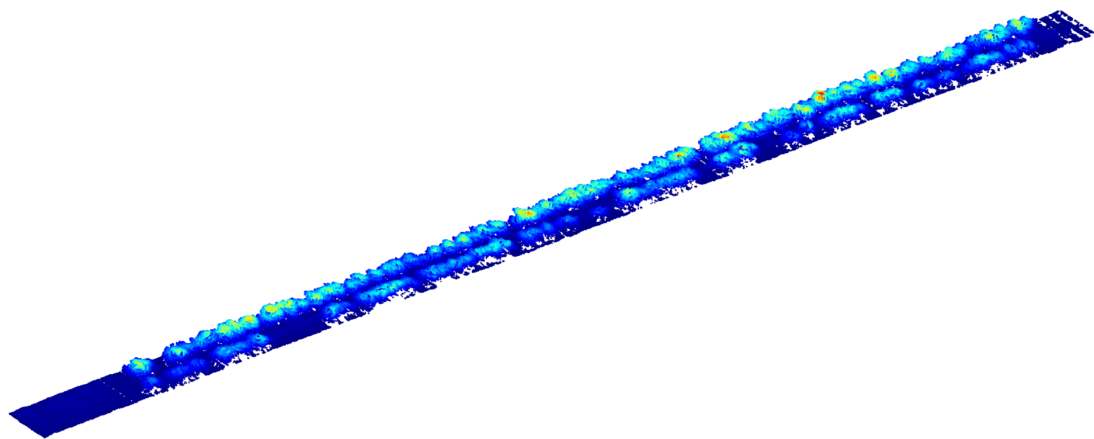


(c)

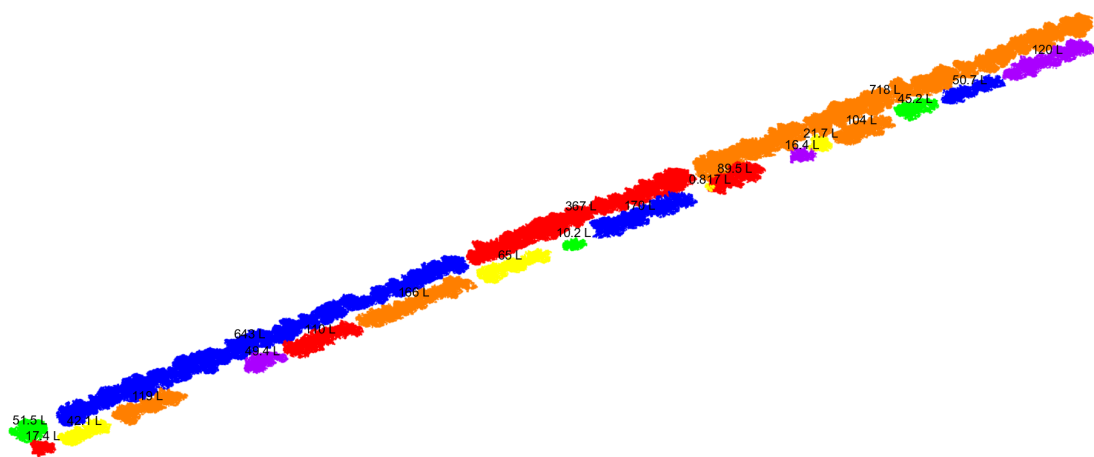
**Figure A.22** Cabbage measurement 10: monoculture. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

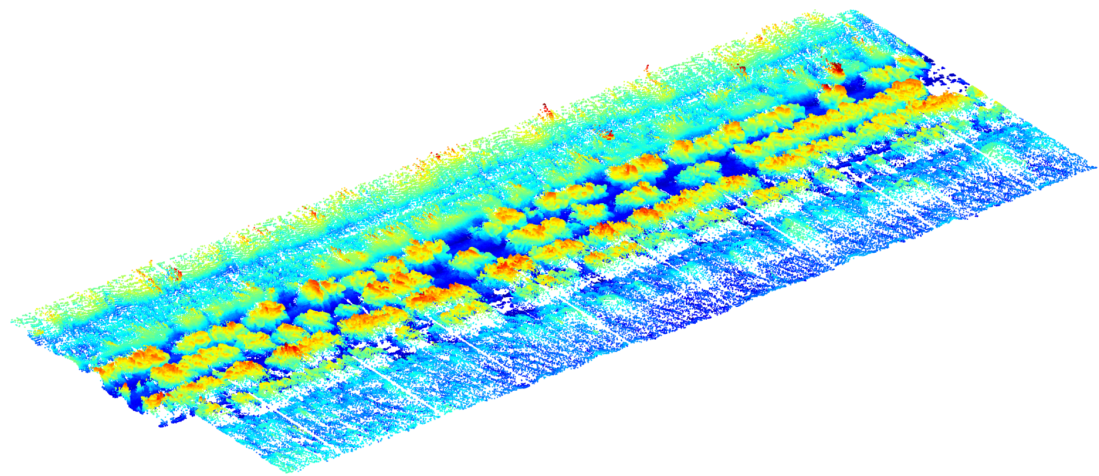


(b)

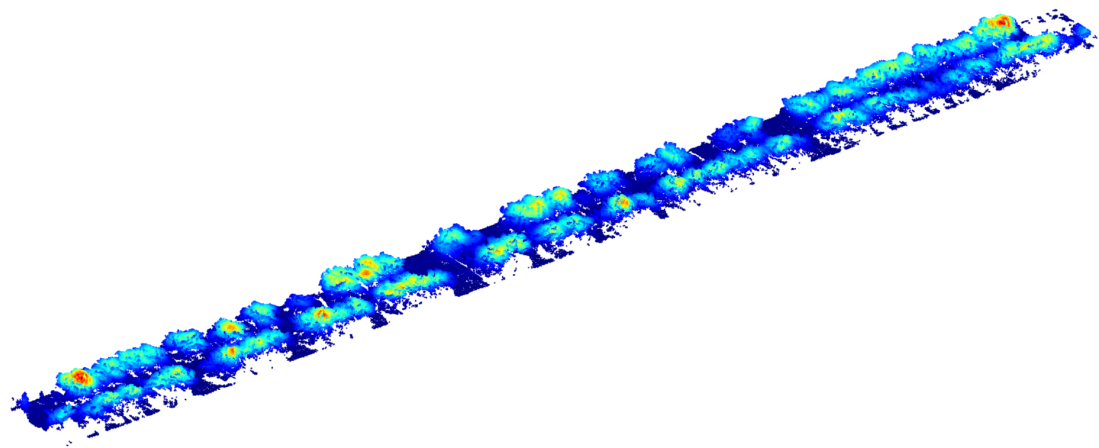


(c)

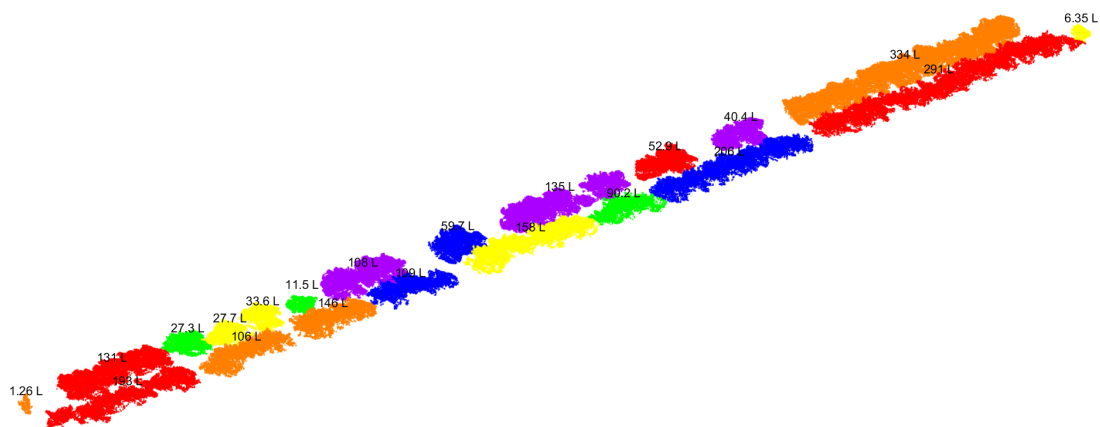
**Figure A.23** Cabbage measurement 11: monoculture. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.



(a)

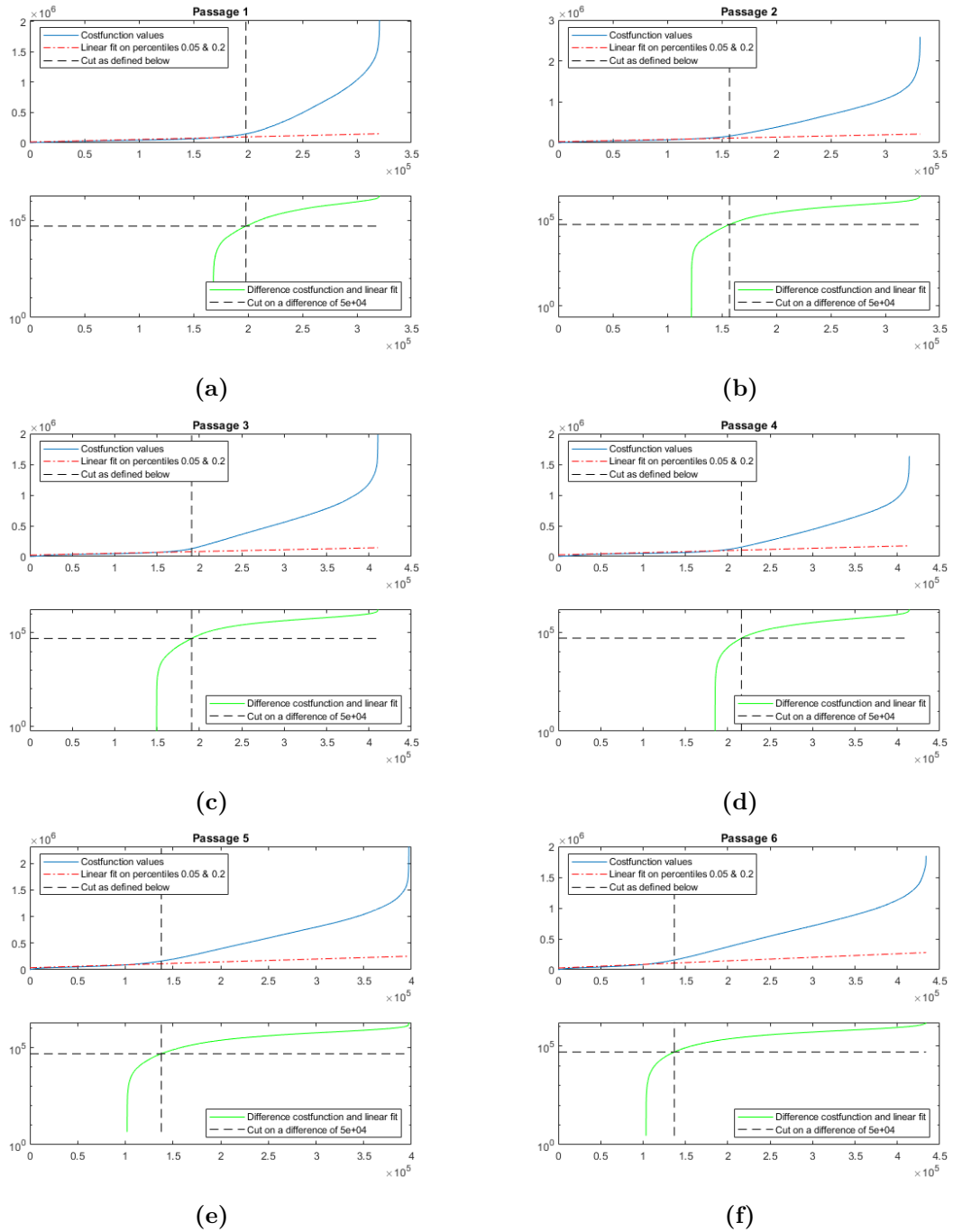


(b)



(c)

**Figure A.24** Cabbage measurement 12: reference strip. (a) Coloured by height, (b) coloured by weighted sum value  $J$ , (c) coloured per cluster, with indicated volume in litre.

A.2.2  $J_s$  and cut-off pointsFigure A.25  $J_s$  curve with linear estimation and cut-off value for all 12 measurements.

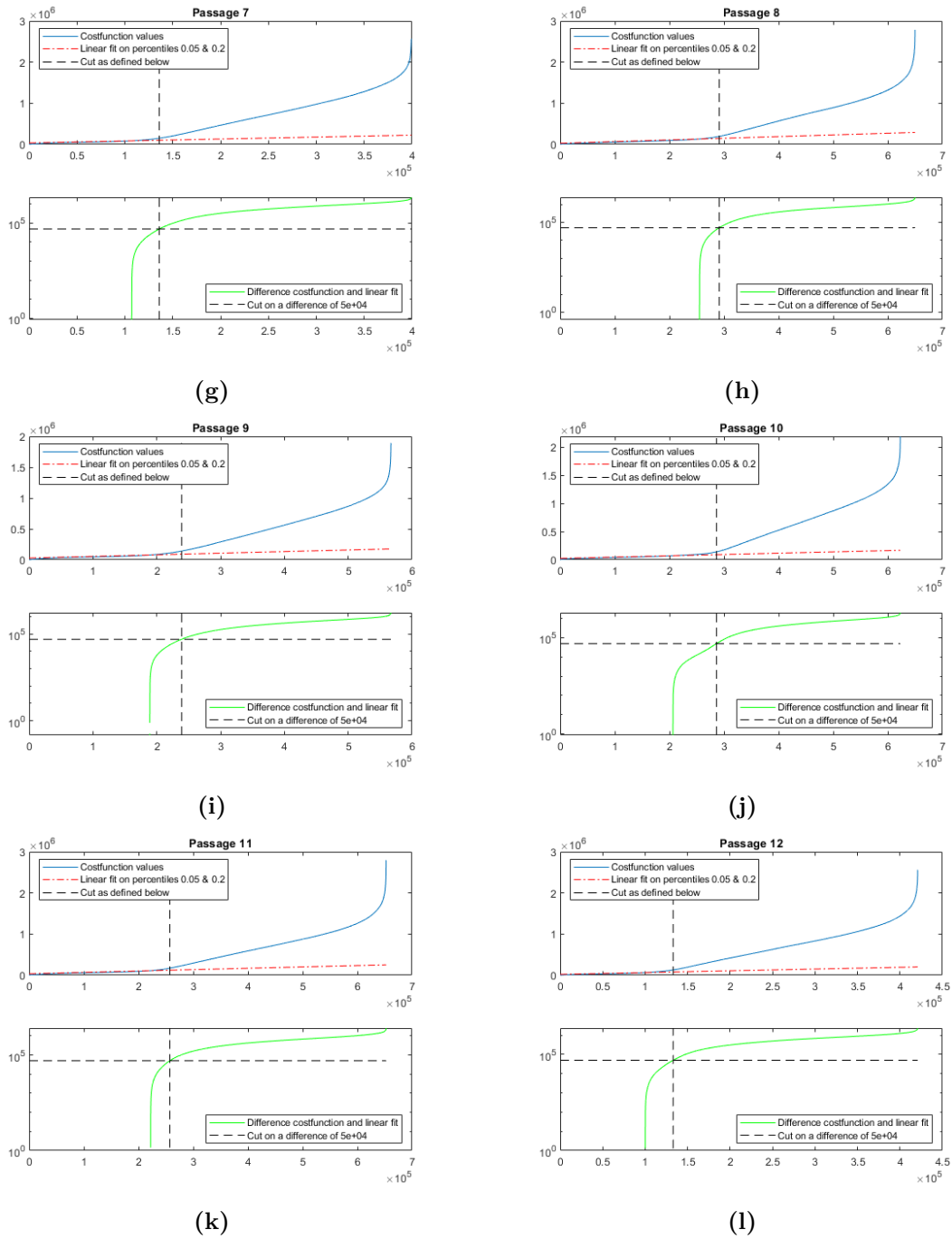


Figure A.25  $J_s$  curve with linear estimation and cut-off value for all 12 measurements (cont.).

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# Conveyor Belt Multi-Spectral Data

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In this appendix, the best images per individual plant per week are included for the indoor experiment described in Chapter 6, alongside the vegetation indices (VI's) and the resulting masks, with and without the application of a Gaussian filter. The pumpkins did not survive until week 6, so another image was taken as a back-up, but as these plants were not followed in the previous weeks this information is disregarded in the analyses. Their results are included here for reference only and did not appear in any of the conclusions drawn in this thesis.

## **B.1 RGB**

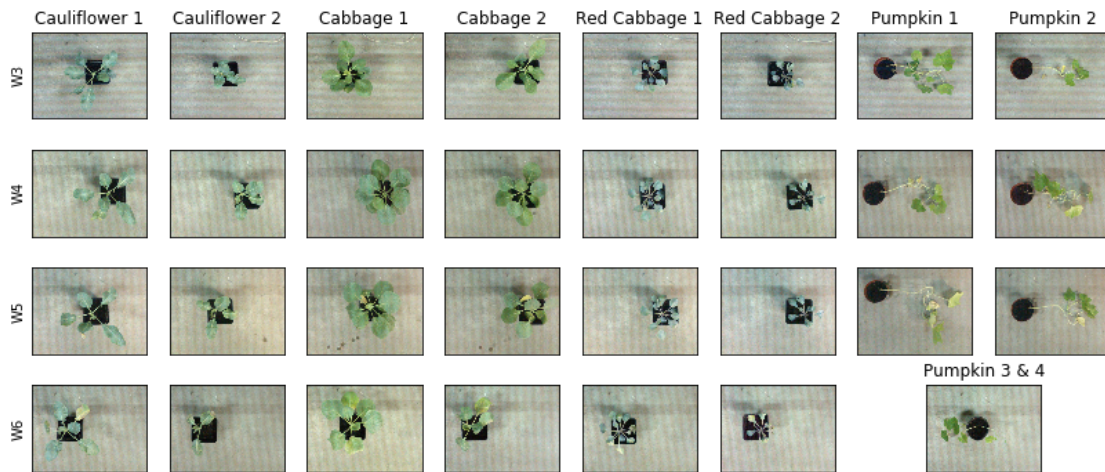


Figure B.1 Original red green blue (RGB) images of all conveyor belt measurements.

## B.2 Vegetation Indices

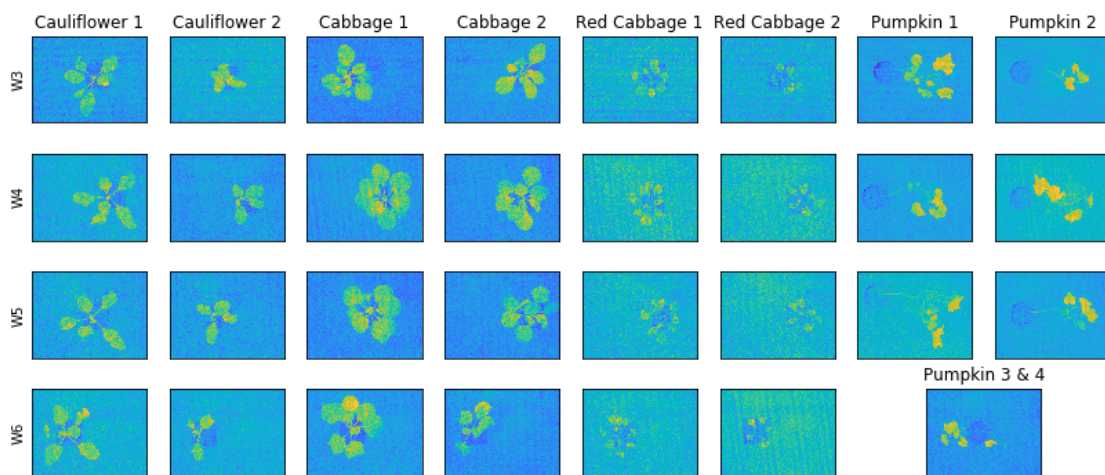
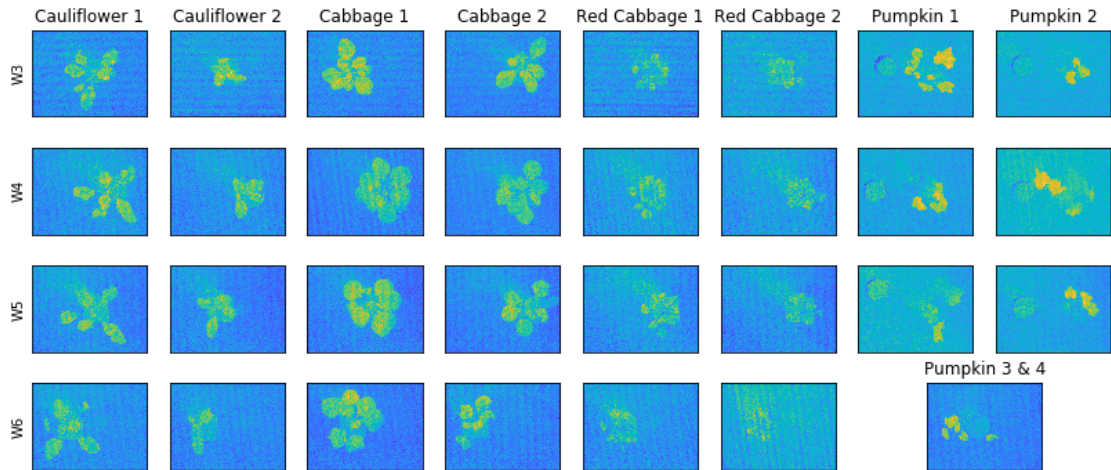
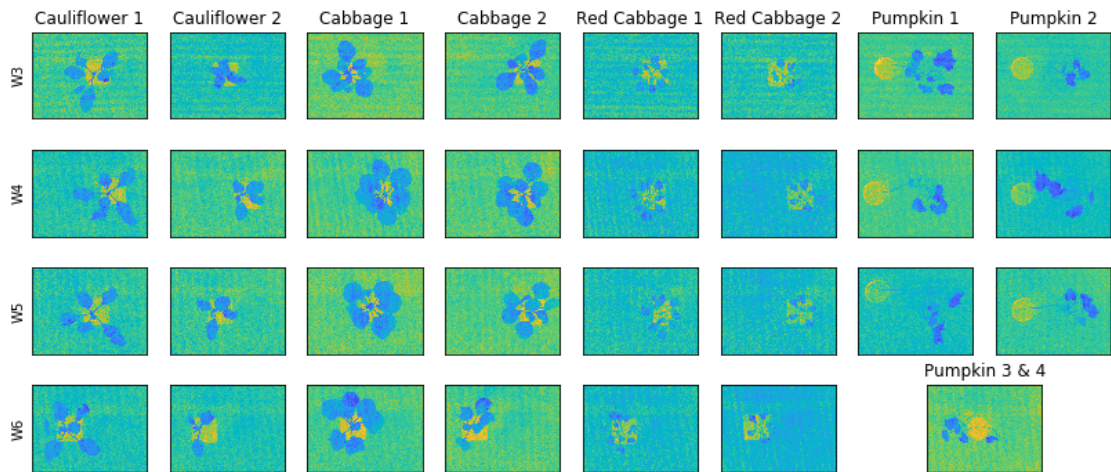


Figure B.2 Excess green (ExG) images of all conveyor belt measurements.



**Figure B.3** Excess green minus excess red (ExGR) images of all conveyor belt measurements.



**Figure B.4** Colour index of vegetation extraction (CIVE) images of all conveyor belt measurements.

## B.3 Histograms of Normalised Indices

### B.3.1 Without Filters

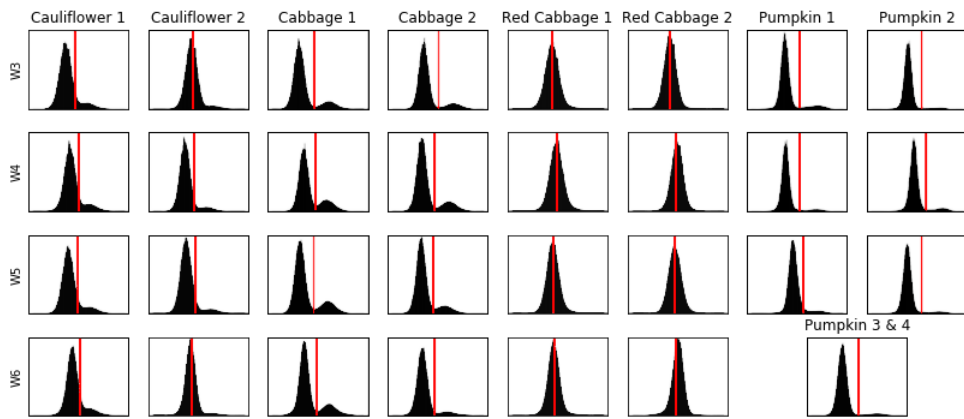


Figure B.5 ExG histograms without filter.

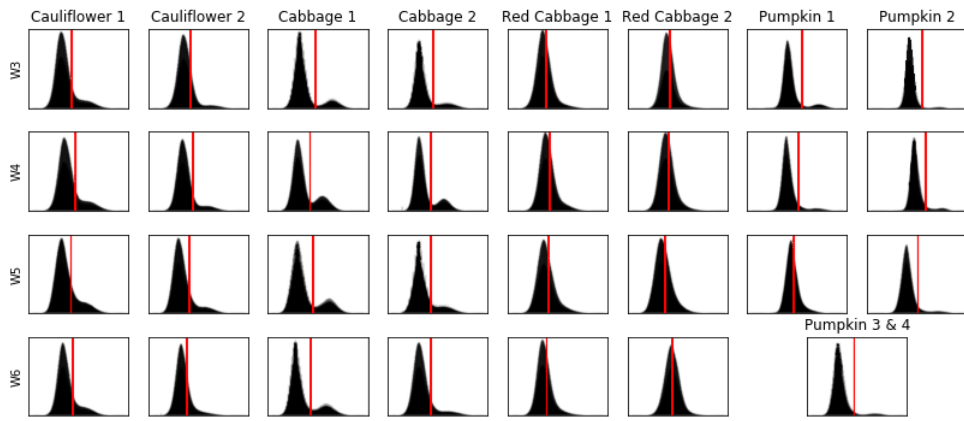


Figure B.6 ExGR histograms without filter.

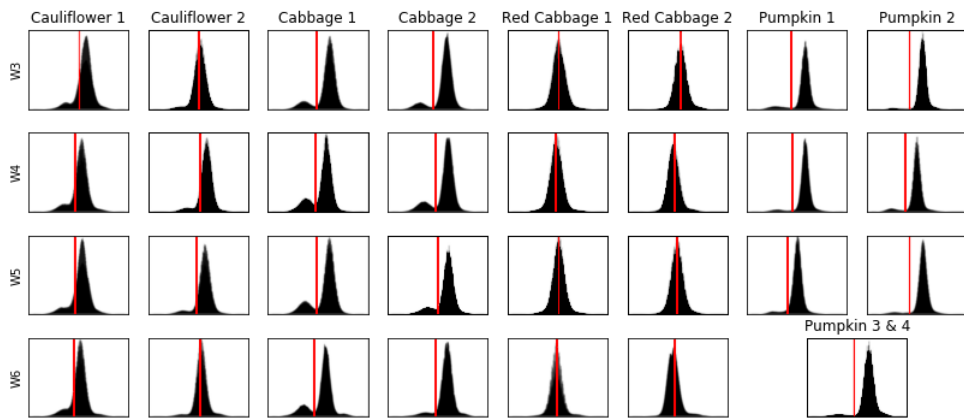


Figure B.7 CIVE histograms without filter.

### B.3.2 With Filters

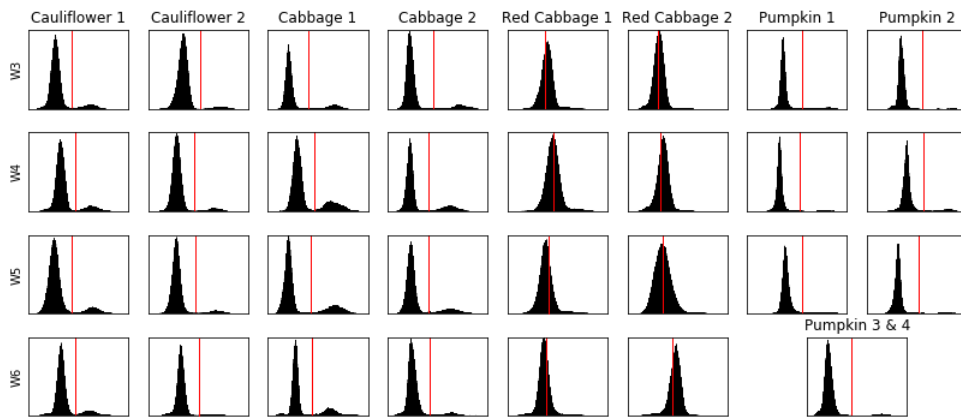


Figure B.8 ExG histograms with filter.

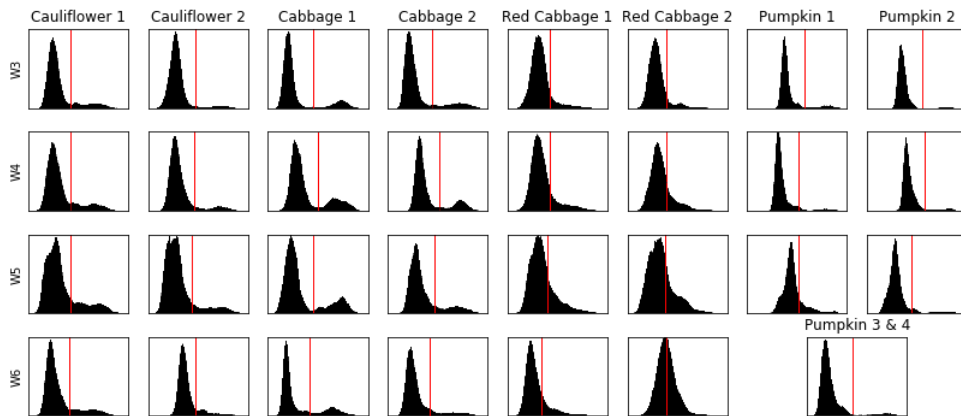


Figure B.9 ExGR histograms with filter.

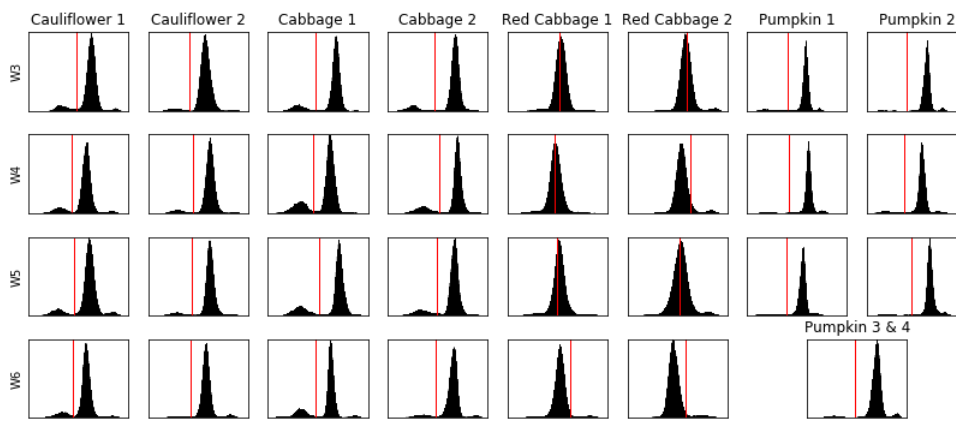


Figure B.10 CIVE histograms with filter.

## B.4 Masks of Normalised Indices

### B.4.1 Without Filters

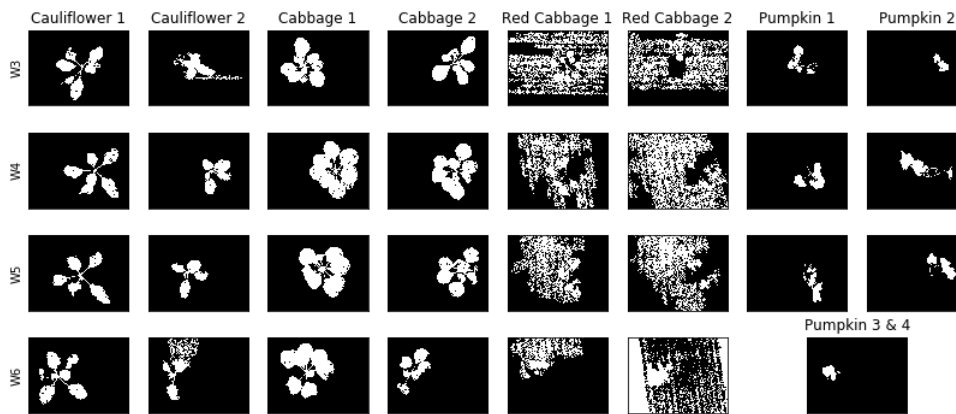


Figure B.11 ExG masks without filter.

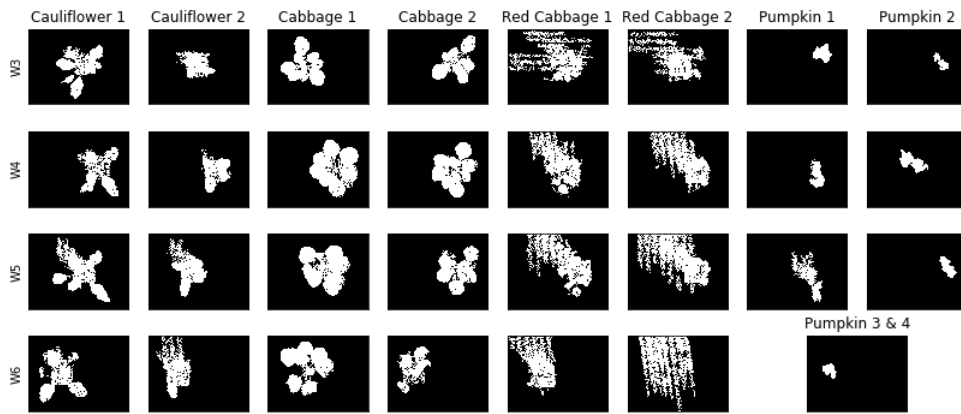


Figure B.12 ExGR masks without filter.

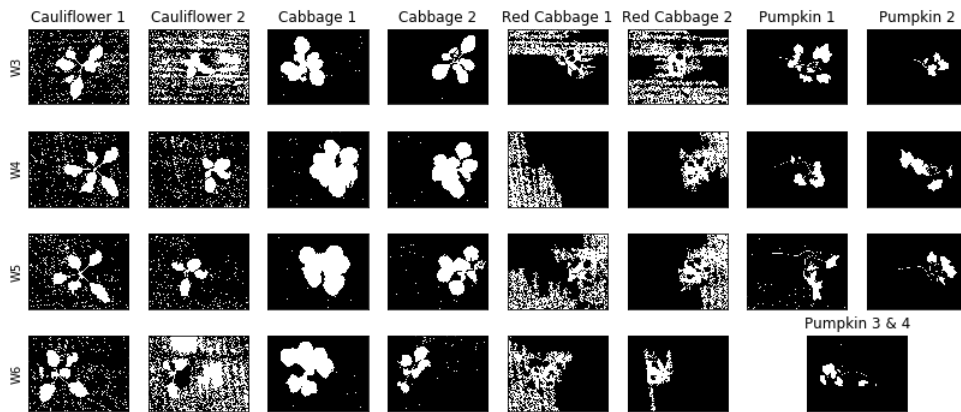


Figure B.13 CIVE masks without filter.

## B.4.2 With Filters

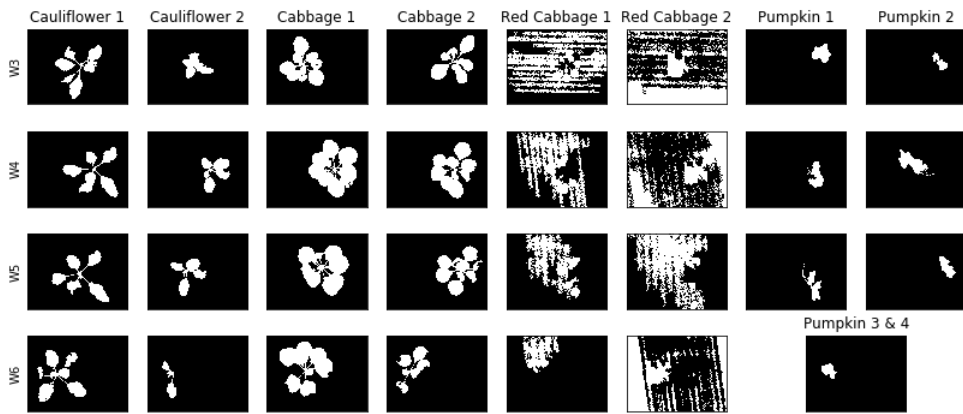


Figure B.14 ExG masks with filter.

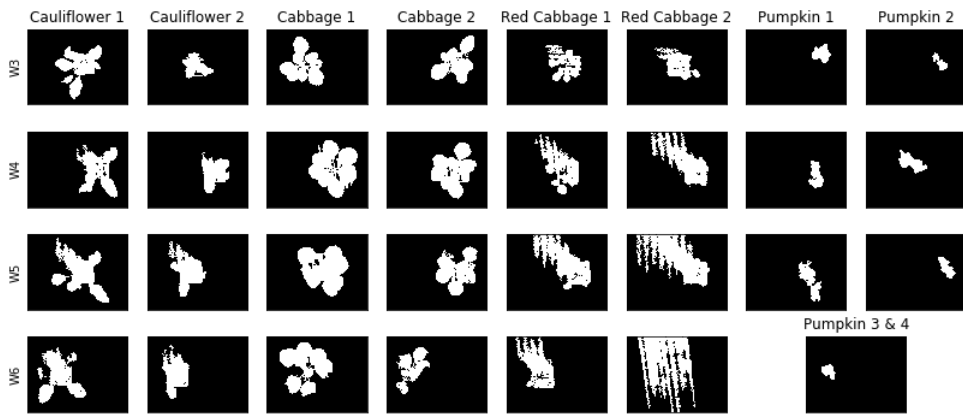


Figure B.15 ExGR masks with filter.

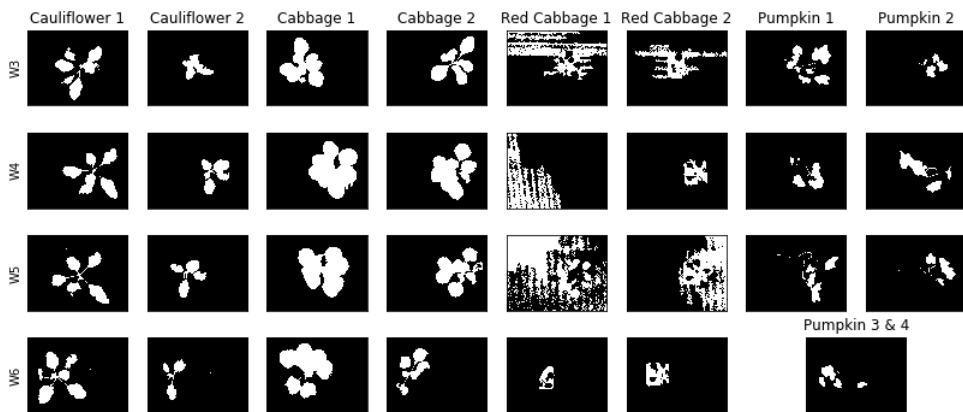


Figure B.16 CIVE masks with filter.

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## Conveyor Belt 3D Data

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The point clouds of the conveyor belt experiment are processed as described in Chapter 10. In this appendix, Section C.1 shows the separate and merged point clouds of a single measurement, before and after denoising. The effects can be seen both in the histograms as well as the resulting vegetation cloud. In Section C.3, the final 3D result, are shown alongside the discarded points in black for all individuals in all weeks. Each of these point clouds is included from an angle as well as straight from above, where the latter are superimposed on the RGB images from Section C.2. Finally, the volumes and projected surface areas of each vegetation cloud are listed in Section C.3.

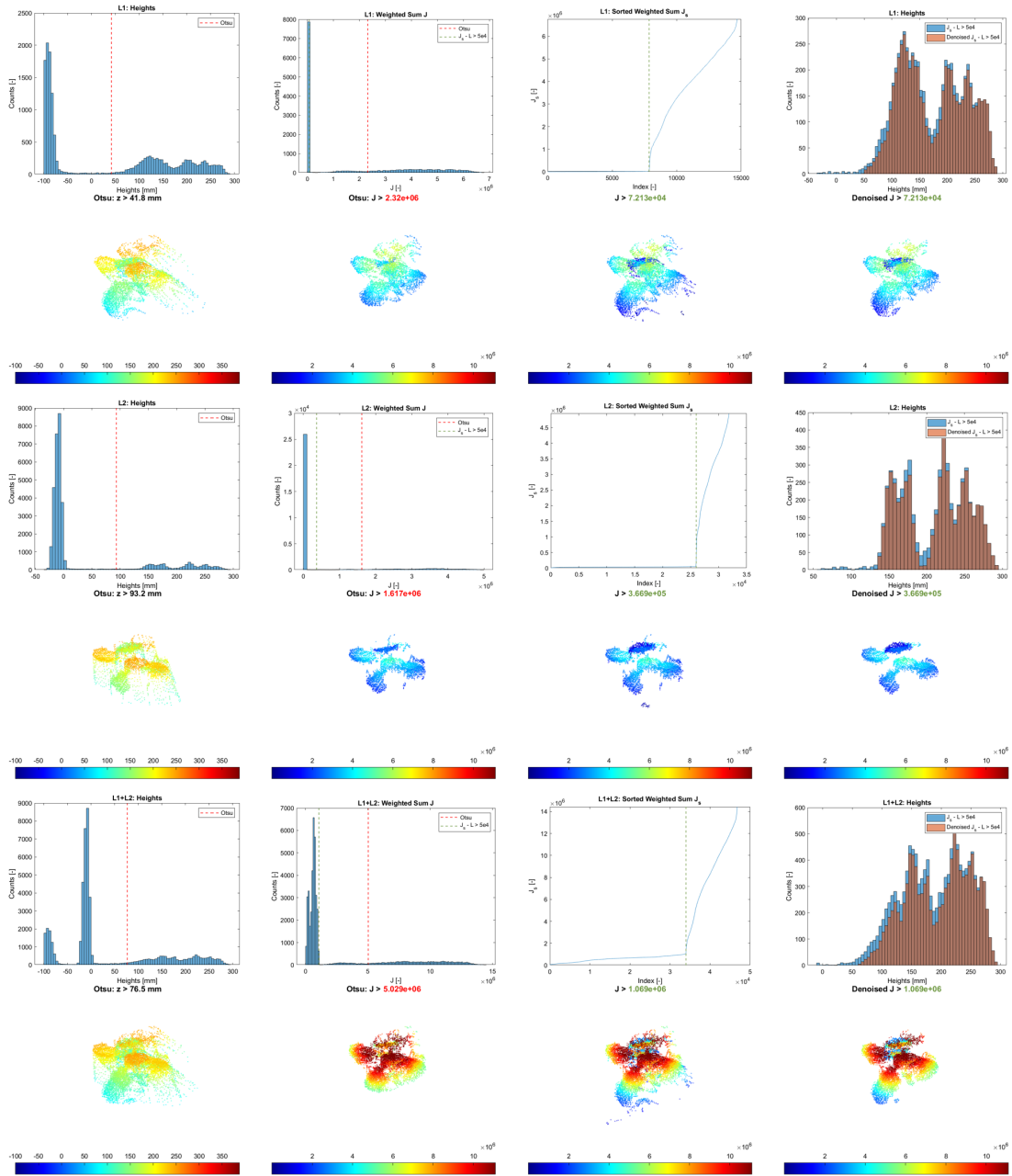
### C.1 Isolating Vegetation Before and After Merging

In Figure C.1 the point cloud of a single measurement of a cabbage is shown. Here, each step in the vegetation isolation progress is performed on both the separate clouds (top and middle rows) as well as the merged point clouds (bottom row). The left-most graph shows the histogram of each of these clouds, with the threshold obtained through Otsu's method indicated in red. The points that meet this criterion are shown in the point cloud image directly below the graph, where the colours indicate height. The second column shows the histograms of the weighted sum values  $J$  as calculated for each situation, with the red line once again indicating the threshold as obtained through Otsu's method. The point clouds in this column show all points that meet this threshold, where colour indicates the value  $J$ . In the third column, the values of  $J$  are sorted to obtain  $J_s$ , where the change in slope between floor points and vegetation is clearly visible, and indicated with a green

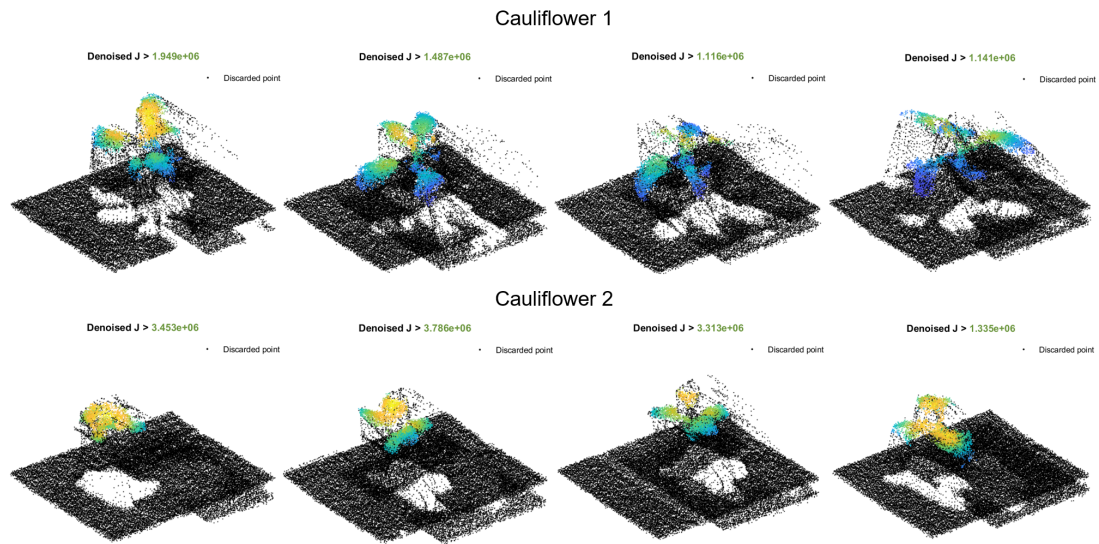
line. This value is also indicated in the second column through a green line for easier comparison, and generally produces a lower threshold value than Otsu's method. The point clouds in the third column contain all points that meet this  $J_s$  based criterion. The final column shows the effect of outlier removal in point cloud form, as well as the height histograms of the final vegetation clouds before and after denoising. When compared to the histograms in the first column, nearly all of the highest values are maintained, while the histogram profile changes towards lower values, where the final obtained point cloud through  $J_s$  frequently reaches values below the originally proposed height boundary, sometimes even after outlier removal. Note that this histogram is not a stacked bar chart, but a superimposed chart, as the denoised values are a subset of the original height values shown in blue.

## C.2 Isolating Vegetation Results

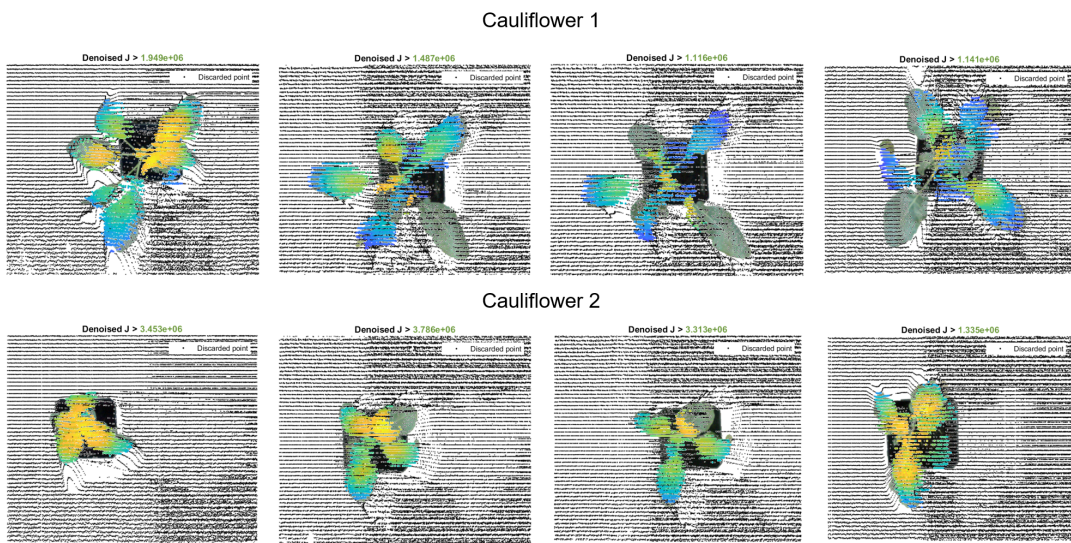
This section shows both the original (black) merged clouds of each individual and the remaining vegetation point clouds (colour). Both cauliflowers are shown in Figure C.2, both red cabbages in Figure C.3, both cabbages in Figure C.4, and the pumpkins in Figure C.5. Each row of four images shows the same individual chronologically, from week 3 to 6, in (a) shown in 3D view, and in (b) in top view, with the points superimposed on the RGB images obtained with the multi-spectral camera (MSC). The missed leaves in cauliflower individual 1 and both cabbages are clearly visible by the lack of points, both coloured and black. Furthermore, in none of the pumpkin measurements the vegetation was reliably identified. All point cloud colouring reflects the  $J$  values on the fixed colour scale used in Chapter 10 and throughout this appendix.



**Figure C.1** Vegetation isolation steps on separate and merged clouds. Top: light detection and ranging sensor (lidar) 1 (pushbroom), middle: lidar 2 (vertical), bottom: merged point cloud. From left to right: height histogram, weighted sum histogram, sorted weighted sum values  $J_s$ , effect of denoising on height histogram of result. Below each graph the corresponding point cloud is included, where the colours in the left-most column correspond to the height values, and all others to  $J$ , where the scaling is fixed to ease comparison.

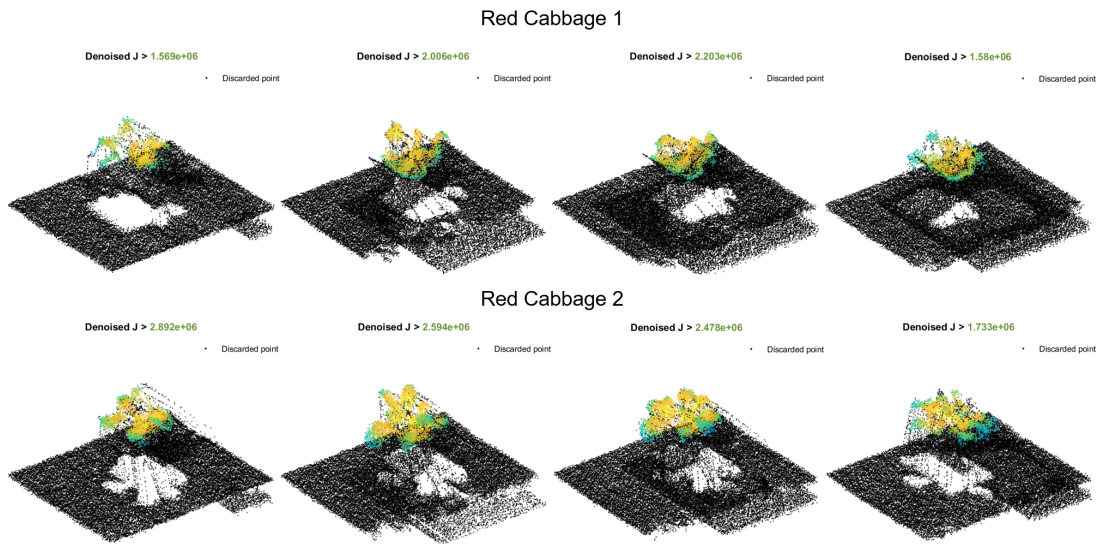


(a)

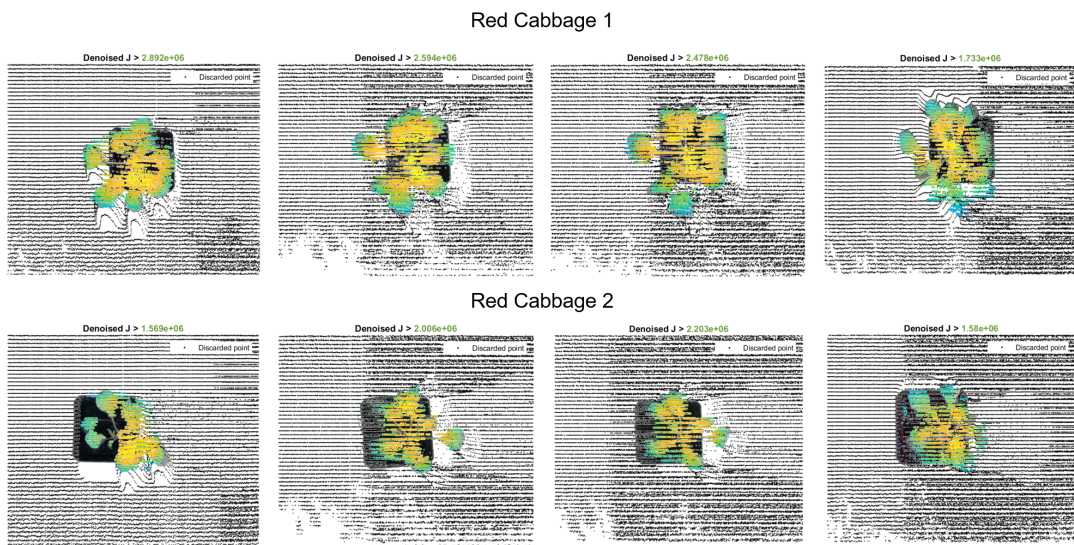


(b)

**Figure C.2** Cauliflower vegetation (colour) amid discarded points (black). The top view (b) is superimposed on the RGB images from Section B.1.

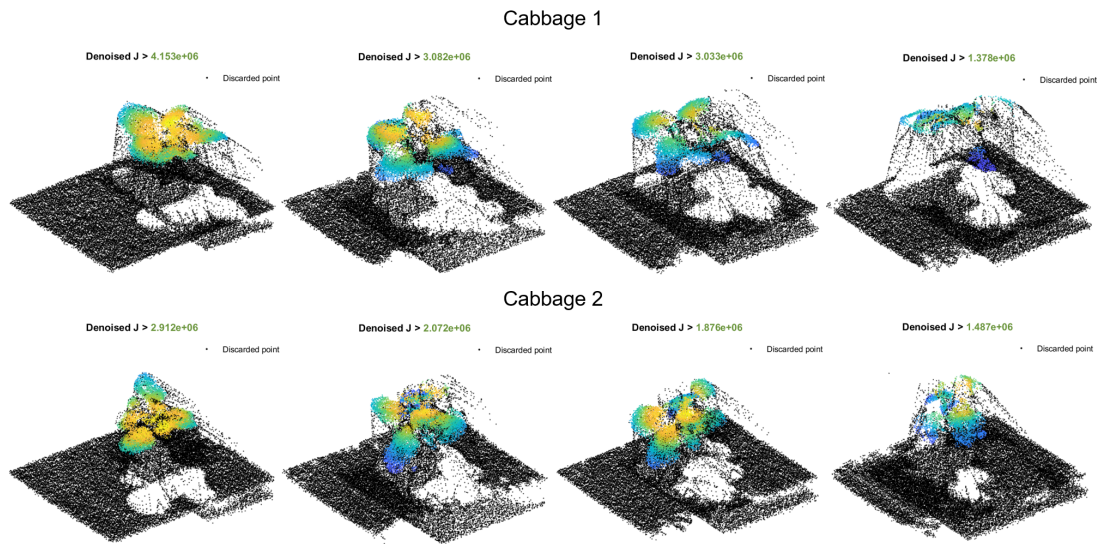


(a)

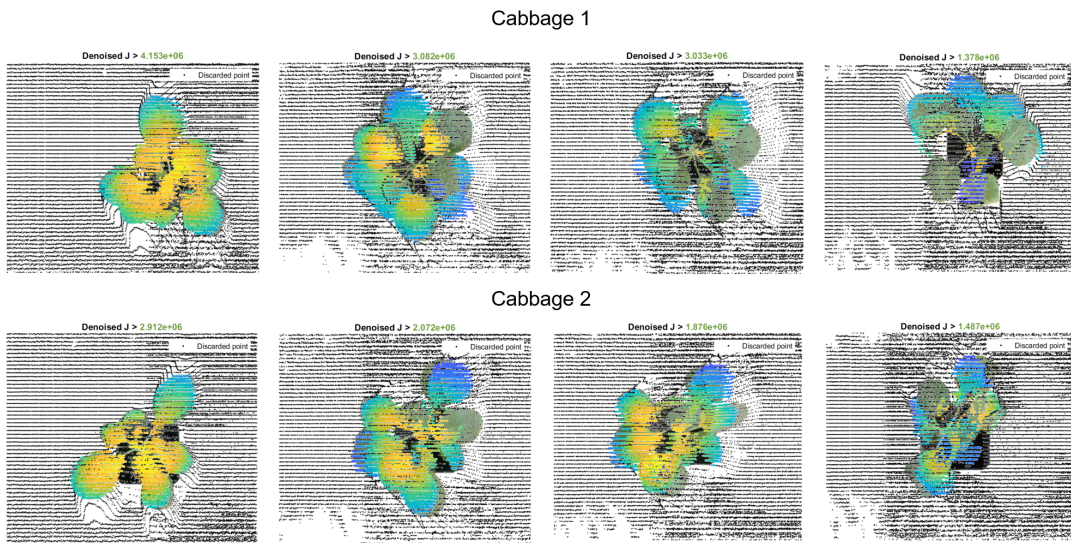


(b)

**Figure C.3** Red cabbage vegetation (colour) amid discarded points (black). The top view (b) is superimposed on the RGB images from Section B.1.

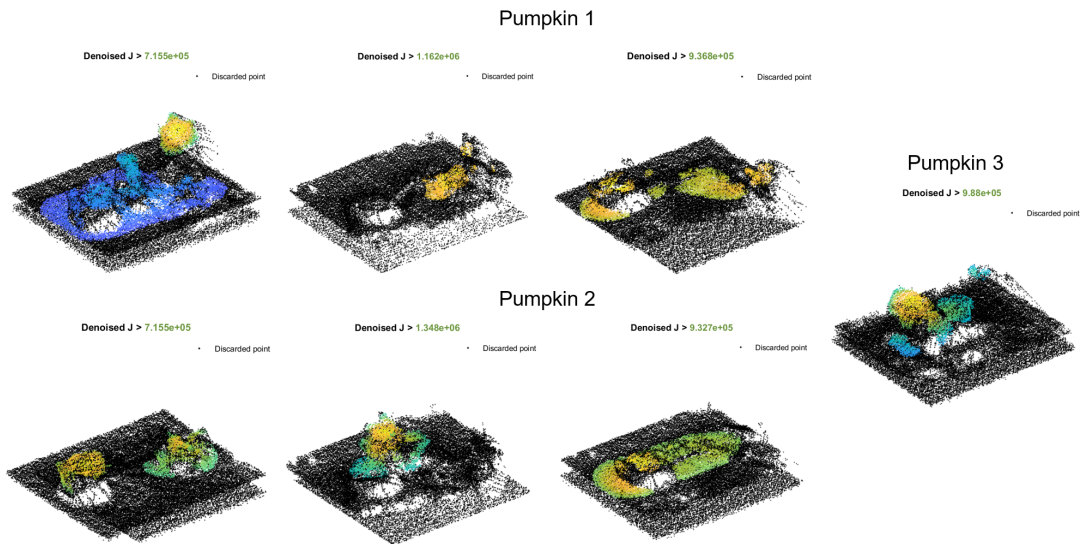


(a)

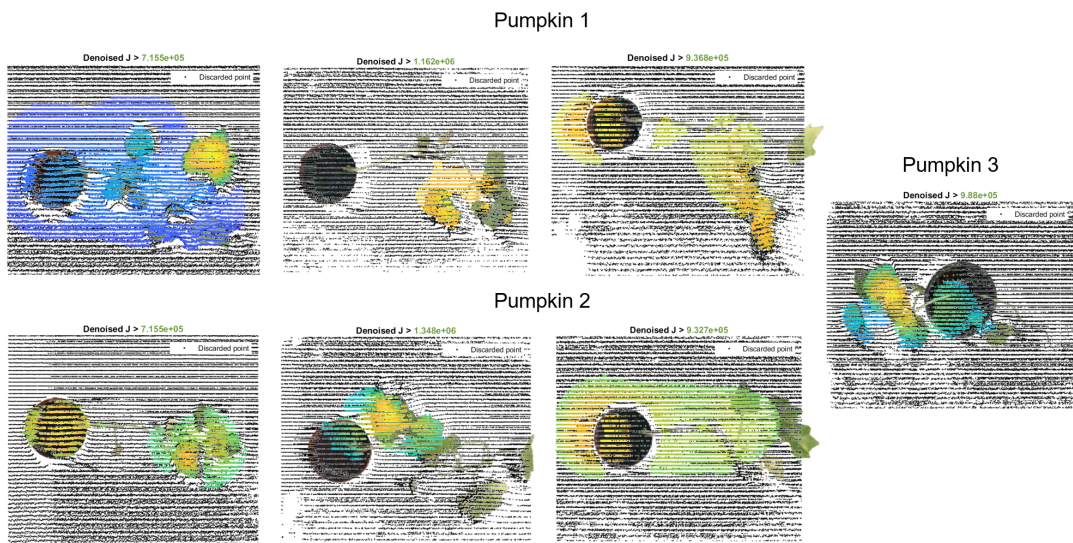


(b)

**Figure C.4** Cabbage vegetation (colour) amid discarded points (black). The top view (b) is superimposed on the RGB images from Section B.1.



(a)



(b)

**Figure C.5** Pumpkin vegetation (colour) amid discarded points (black). The top view (b) is superimposed on the RGB images from Section B.1.

### C.3 Vegetation Metrics

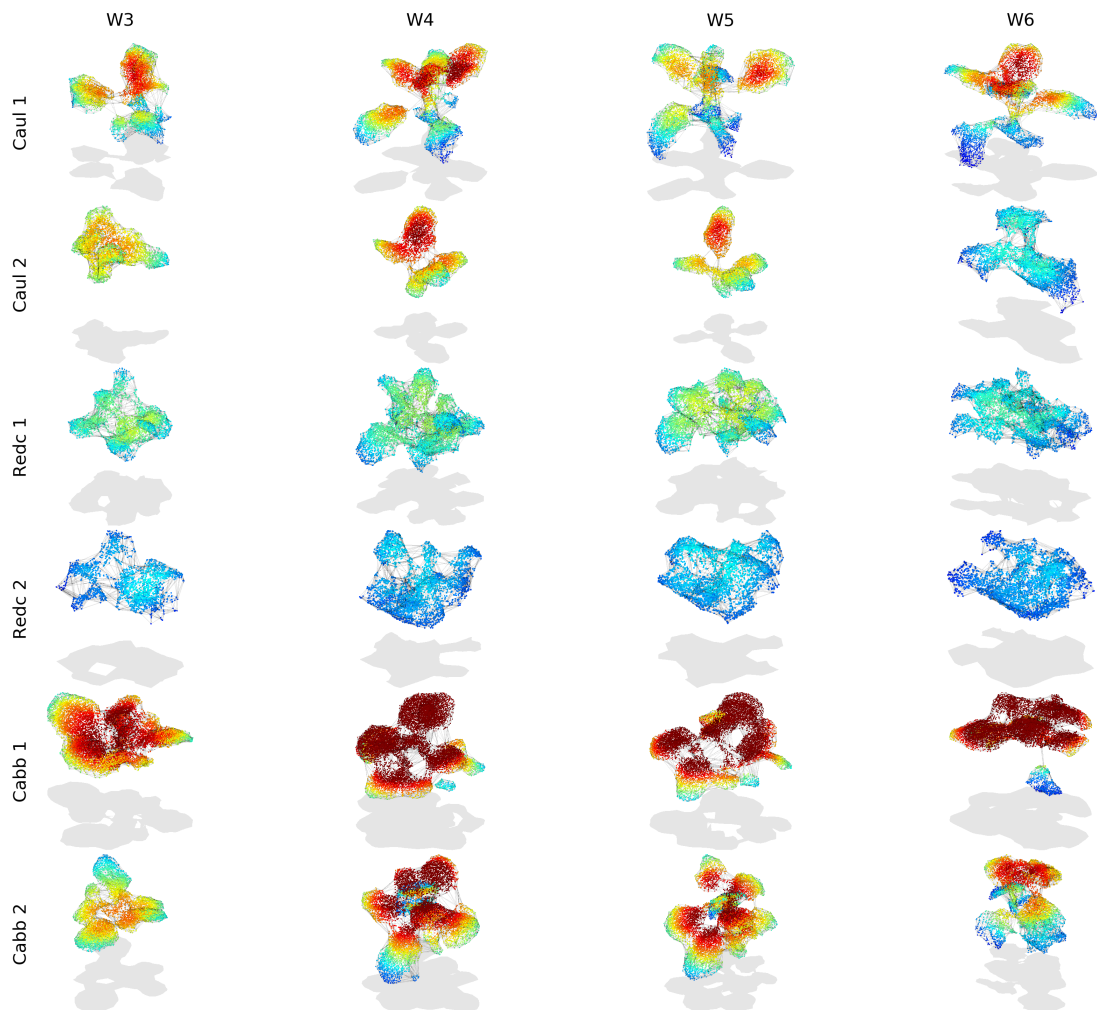
The vegetation point clouds from the previous section are converted to a volume by a boundary function with maximal shrink factor, the edges of which are shown as black lines in Figure C.6. The covered soil area is also extracted from this volume, as visualised by the grey area shown below each volume. The resulting volumes in litre and areas in  $\text{mm}^2$  are listed in Tables C.1 and C.2 respectively.

**Table C.1** Volumes of vegetation clouds in litres.

	<b>W3</b>	<b>W4</b>	<b>W5</b>	<b>W6</b>
Cauliflower 1	1.81	2.00	2.11	2.04
Cauliflower 2	0.546	0.629	0.539	1.28
Red Cabbage 1	1.04	0.990	1.06	0.981
Red Cabbage 2	0.896	0.886	0.731	0.949
Cabbage 1	1.49	2.95	2.58	2.62
Cabbage 2	1.05	2.73	1.84	1.29

**Table C.2** Areas of vegetation clouds in  $\text{mm}^2$ .

	<b>W3</b>	<b>W4</b>	<b>W5</b>	<b>W6</b>
Cauliflower 1	47425	45572	42213	51845
Cauliflower 2	15747	21392	21195	30321
Red Cabbage 1	30217	30766	34986	32226
Red Cabbage 2	24205	19667	18271	23535
Cabbage 1	56608	71418	57891	67921
Cabbage 2	41277	54851	53819	40011



**Figure C.6** Volumes (black lines) and areas (grey patch) of all vegetation point clouds (coloured).

