Supplementary material

Figure S1: Test of maximum flying altitude

The accuracy of flying altitude was tested by flying over circles of 40 cm in radius (0.53 m^2) placed approximately 5 m apart in the field. The flying speed was 3 m/s and the altitude was increased from 2-5 m. 15 replications were made for each altitude.

Figure S1a. Overview of setup to test maximum flying altitude.

Figure S1b. Aerial photo of the test circle (0.53 m^2) from 3 m altitude. Two droppings are visible.

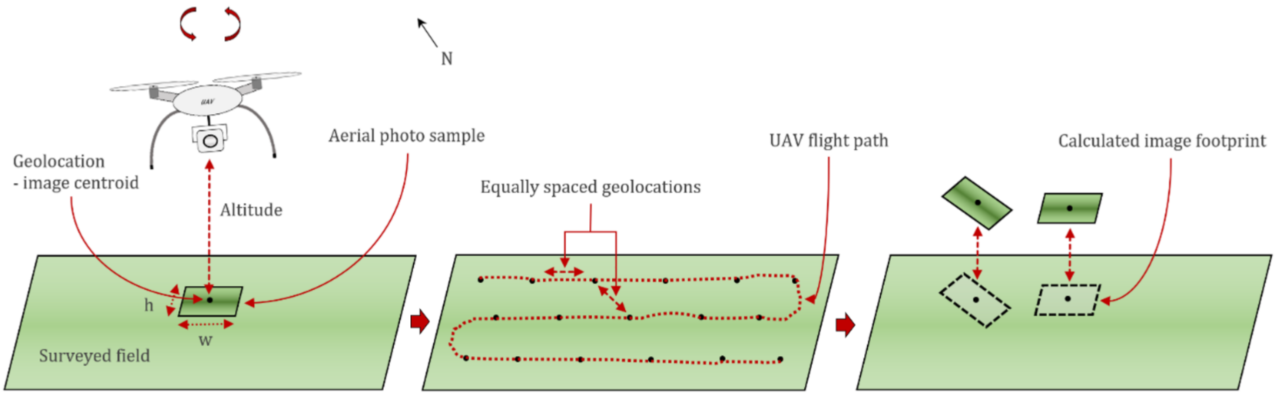
Supplementary Material S2: Revised protocol - preparation, extraction and georeferencing of single UAV images

By flying at altitudes below 10 m it was not possible to automatically create orthomosaics via software such as DroneDeploy or Pix4Dcapture of the aerial photos [1]. Consequently, it was necessary to develop a suitable practical procedure for georeferencing the UAV photos to obtain usable results, which would also be applicable for similar future studies. Further flying in the Pix4DCapture Free Flight mode resulted in photos unequally scattered across the field. In order to create a grid of regular spaced photo samples, thinning by the GPS location of the photo centroid contained in the metadata was necessary. This preparation of the raw data involved three major steps consisting of:

i) Retrieval of metadata contained in the aerial photos

ii) Creation of a surveying grid with regular spaced photo samples

iii) Generation of Esri world file image extensions in order to enable georeferencing in GIS software



i) Initial raw UAV data sampling of image with corresponding metadata

ii) Creation of regular grid of equally spaced image samples

iii) Georeferencing by generation of image world file from extracted metadata and spatial transformations

i) Retrieval of metadata contained in aerial photos

In order to analyse the UAV captured aerial photos and ultimately enabling georeferencing, information tags stored as metadata for each photo were extracted. This was achieved by using the program exiftool.exe (version 11.42) computed in R software using the base function “system2” [2,3]. The metadata included GPS coordinates of each photo centroid, the barometric altitude of the UAV, the orientation of the photo as the relative deviation from true north, both focal length and sensor width of the camera, and dimensions in pixels of the picture (Table S1).

Table S1: The extracted metadata used for preparation and georeferencing of the UAV photos.

Metadata	Unit
Relative Altitude	meters (m)
GPS longitude	Degrees (deg)
GPS latitude	deg
Gimbal Yaw Degree (Deviation of the camera from true North)	deg
Image Height	pixels
Image Width	pixels
Focal Length	Milimeters (mm)
Sensor Width	mm

ii) Creation of an initial surveying grid with regular spaced photo samples

The semi manual horizontal piloting of the UAV in the Pix4Dcapture Free Flight mode resulted in photos with unequally scattered geolocation across the field. To create a representative sampling of the dropping densities, it was therefore essential to execute a thinning procedure for the large number of closely spaced aerial photos (in average exceeding 1000 photos per field), to ensure a regularly spaced grid of photo samples at equal intervals from the surveyed field (Figure S1.a-b). To this end the GPS location of the photo centroid contained in the metadata was necessary. The following operations were executed:

1) Firstly, the point coordinates of the photo centroid were imported into ArcMap (version 10.5.1, Advanced License) via the Geotagged Photo to Point tool.

2) The coordinates of each point were then transformed from degrees (latitude, longitude) into UTM (Universal Transverse Mercator) coordinates by the Data Management Tool, Add XY Coordinates.

3) Finally thinning of the data table for each field containing the processed photo points was achieved using the Delete identical tool in ArcMap with a x, y tolerance of 5 to 20 meters (Appendix III) [4].

4) After a subsequent georeferencing it was possible to estimate the upper limit for a final representative thinning of the aerial photos.

Figure S2.a: Surveyed field before equal spacing and thinning procedure.

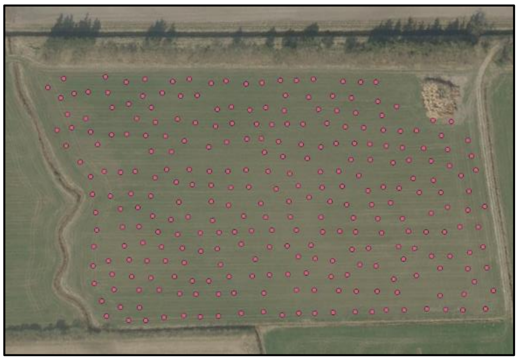


Figure S2.b: Surveyed field after equal spacing and thinning procedure.

iii) Georeferencing of UAV aerial photos by generation of world files

The procedure for georeferencing of the aerial images was derived from descriptions in two independent studies from 2014 [5] and 2015 [6], but with several modifications. All calculations were done in R software [7].

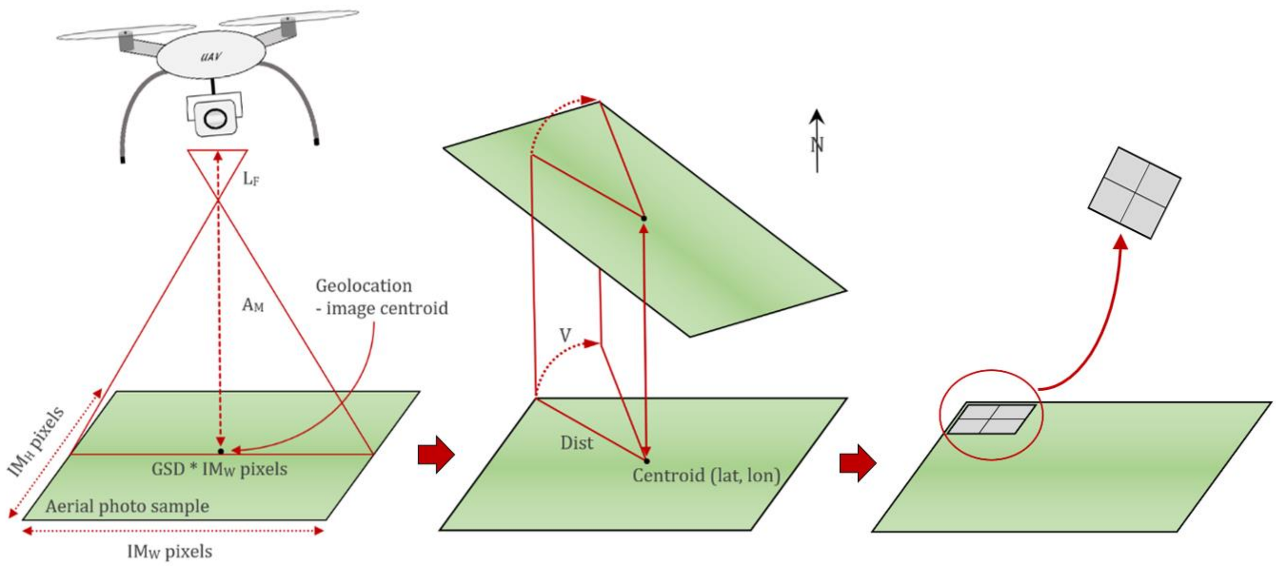
To practically perform georeferencing of the photos and concludingly project them as rasters in QGIS (version 3.4.1) a world file (JGW) extension was generated for each aerial image (JPG). The procedure and format of the world file followed the criteria established by Esri (Esri, Redlands, CA, US). Parameter A and E describe the dimensions of each pixel on the image (Table S2). Parameter D and B denotes the rotation of the images, obtained by triangulating from the absolute deviation from north extracted from the photo metadata (Gimbal Yaw Degree). Parameter C and F denotes the spatial coordinates in the UTM format (Universal Transverse Mercator).

Table S2: Parameters included in the generated worldfile enabling georeferencing of the UAV photos [4]. Pixel sizes are measured in millimetres (mm) and rotation in degrees (deg). The coordinates are measured UTM format (Universal Transverse Mercator)

Line	Parameter	Unit
1	A: pixel size in the x-direction in map units/pixel	mm
2	D: rotation about y-axis	deg
3	B: rotation about x-axis	deg
4	E: pixel size in the y-direction in map units	mm
5	C: x-coordinate of the centre of the upper left pixel	UTM
6	F: y-coordinate of the centre of the upper left pixel	UTM

An Esri world file was generated for each of the UAV obtained aerial photos, of the settled 10 x 10 meter image spacing, numbering 2523 images in total for all 10 fields surveyed in this study. The applicability of the world files was tested in both QGIS and ArcGIS software, which proved successful.

To meet the requirements to the format of the Esri worldfile the following calculations and format transformations of the extracted metadata were necessary. The calculations followed the formula presented by Pix4Dcapture (version 4.5.0, Pix4D S.A., Switzerland) for Phantom 4 Pro and Phantom 3 Pro combined with the corrected Field Of View (FOV) table for the used UAV's [8,9].



1) Parameters used to calculate the image footprint. The only changeable variable is the flying altitude (A_m).

2) Spatial transformations are done to define the distance (Dist) from centroid to upper left corner. This is found by trigonometry of image dimensions and deviations in orientation to true north measured by the angle V.

3) The precise parameters for the pixel in the uppermost left corner of the image can now be obtained and Esri world files generated.

World file layout

Line	Parameter	Unit
1	A: pixel size in the x-direction in map units/pixel	mm
2	D: rotation about y-axis	deg
3	B: rotation about x-axis	deg
4	E: pixel size in the y-direction in map units	mm
5	C: x-coordinate of the center of the upper left pixel	UTM
6	F: y-coordinate of the center of the upper left pixel	UTM

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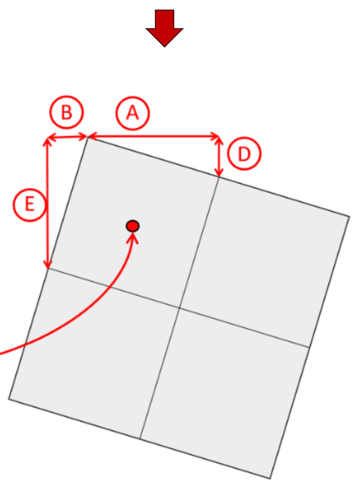

4) With all calculations done the layout of the world file can be filled in with all parameter's representative for the uppermost left pixel of the image.

Formulas and calculations

1) Ground sampling distance (GSD) and image footprint (m^2)

Firstly, the image footprint was calculated by finding the ground sampling distance (GSD), thereby enabling determination of the area in m^2 covered by each UAV image. Ground sampling distance (GSD) is defined as cm / pixel on the ground and calculations were performed, where the sensor width (mm) of the camera was denoted as W_S, focal length as L_F, image width as W_{IM} and flight altitude in meter as A_m. The covered area in m^2 could now be calculated by multiplying GSD with the number of pixels in image width (IM_W) and height (IM_H) resulting in the image footprint, which is the distance covered on the ground by one image in width and height direction:

$$GSD = \frac{W_S * A_m * 100}{L_F * W_{IM}} \qquad m^2 = \frac{GSD * IM_W}{100} * \frac{GSD * IM_H}{100}$$

[8]

2) Spatial transformations and triangulations

Formula for calculations of the parameters in the world file were as follows, where the distance from the photo centroid to a given corner of the photo was calculated as *Dist*, where h is the height of the photo and w is the width of the photo. To find the angle (*V*) used to calculate the spatial location of the upper-left corner pixel the following argument was used:

$$Dist = \sqrt{\left(\frac{1}{2} * \mathrm{h}\right)^2 + \left(\frac{1}{2} * \mathrm{w}\right)^2} \qquad V = \cos^{-1} \frac{h^{\frac{1}{2}}}{\sqrt{Dist}}$$

(Eq. S2.2)

Finally, the UTM coordinates *(*Northing and Easting) of the image corner could be defined, by accounting for the angle of deviation from true north (V_n):

$$\mathrm{Northing} = \mathrm{Dist} * \cos \mathrm{V} - \mathrm{V_n}$$

$$\mathrm{Easting} = \mathrm{Dist} * \sin \mathrm{V} - \mathrm{V_n}$$

(Eq. S2.3)

3) Creation of world files

An automated R workflow were established capable of creating world file extension for all images contained in a given folder. World files were carefully written to the same folder containing the images. Finally, after the georeferencing of the aerial photos from the 10 fields, the single images were then loaded into QGIS as rasters with the world file (JGW) extension (Figure S3). Goose droppings on each of the 10 fields were identified and marked individually in QGIS using a shapefile point layer.

References

1. Hawkins, S. Using a drone and photogrammetry software to create orthomosaic images and 3D models of aircraft accident sites. *Isasi* **2016**, 1–26.

2. Hughes, A.; Teuten, E.; Starnes, T.; Cowie, N.; Swinfield, T.; Humpidge, R.; Williams, J.; Bridge, D.; Casey, C.; Asque, A.; et al. Drones for GIS – Best Practice 2018, 2–45.

3. Harvey, P. ExifTool Tag Names Available online: http://owl.phy.queensu.ca/~phil/exiftool/TagNames/index.html.

4. Esri "FAQ: What is the format of the world file used for georeferencing images? Available online: https://support.esri.com/en/technical-article/000002860.

5. Hemerly, E.M. Automatic georeferencing of images acquired by UAV's. *Int. J. Autom. Comput.* **2014**, *11*, 347–352, doi:10.1007/s11633-014-0799-0.

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7. R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2022.

8. Pix4Dcapture Ground Sampling Distance (GSD) Available online: https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-calculator.

9. Pix4Dcapture Camera data sheet Available online: https://www.pix4d.com/product/pix4dmapper-photogrammetry-software.

Figure S3: Examples of photo points and the georeferenced photos in the fields

Field 3:

All photos before regular thinning

After regular thinning (10x10 m spacing)

Figure S3a. All photos before regular thinning (left) and after regular thinning (10x10 m spacing) (right).

Field 3:

(c) With georeferenced aerial photos with 10 m spacings between each other

Figure S3b. Photos spacing after regular thinning (10x10 m spacing).

Field 7 and 8:

(d) All photos before regular thinning

(e) After regular thinning (10x10 m spacing)

Figure S3c. All photos before regular thinning (left) and after regular thinning (10x10 m spacing) (right).

Field 7 and 8:

With georeferenced aerial photos with 10 m spacings between each other

Figure S3d. Photos spacing after regular thinning (10x10 m spacing).

Field 9:

All photos before regular thinning

After regular thinning (10x10 m spacing)

Figure S3e. All photos before regular thinning (left) and after regular thinning (10x10 m spacing) (right).

Field 9:

With georeferenced aerial photos with 10 m spacings between each other (only part of the field is shown).

Figure S3f. Photos spacing after regular thinning (10x10 m spacing).

Field 10:

All photos before regular thinning | After regular thinning (10x10 m spacing)

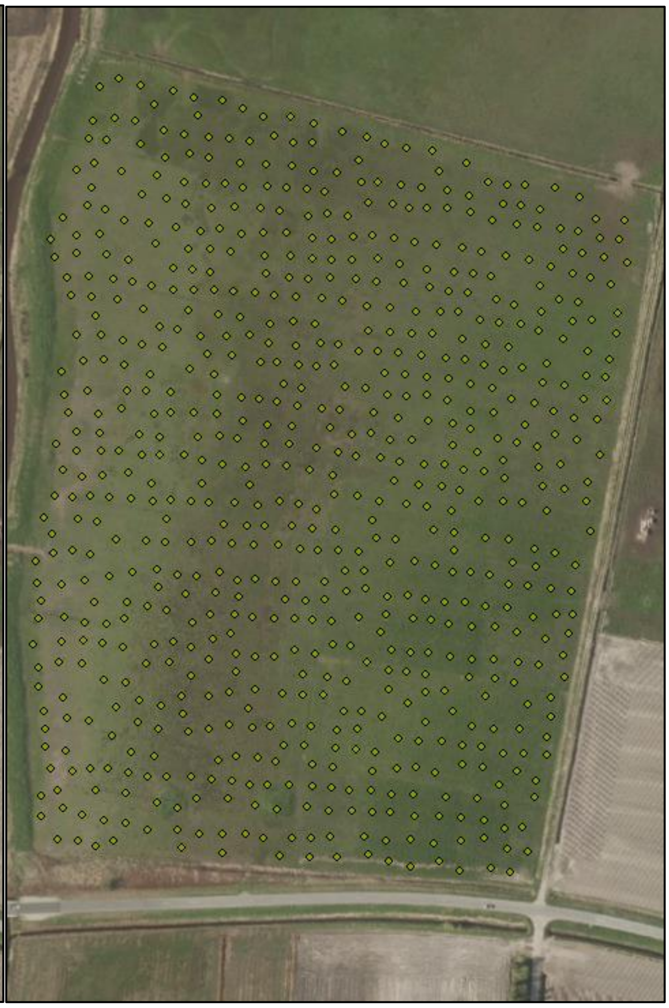

Figure S3g. All photos before regular thinning (left) and after regular thinning (10x10 m spacing) (right).

Field 10:

With georeferenced aerial photos with 10 m spacings between each other.

Figure S3h. Photos spacing after regular thinning (10x10 m spacing).

Figure S4 and Table S3: Accuracy with different flying altitudes

Below are presented the results for dropping counts inside the test circles, when flying at altitudes of 2-5 m compared to the ground count (Table S3).

Table S3. The accuracy and 95% confident intervals as function of the flying altitude of the UAV. 15 replicates were used for the estimation.

Altitude m	Accuracy %	95% confidence interval
0	100	0
2	93	[0.87;0.98]
3	88	[0.81;0.95]
4	66	[0.53;0.79]
5	58	[0.39;0.76]

To test for significant differences the accuracy of flying altitude was tested with an ANOVA and Tukey post hoc test (figure S4). This resulted in non-significant differences between ground count (0 m) and 2 and 3 m. For the remaining flying altitudes comparisons to the ground count were significantly different.

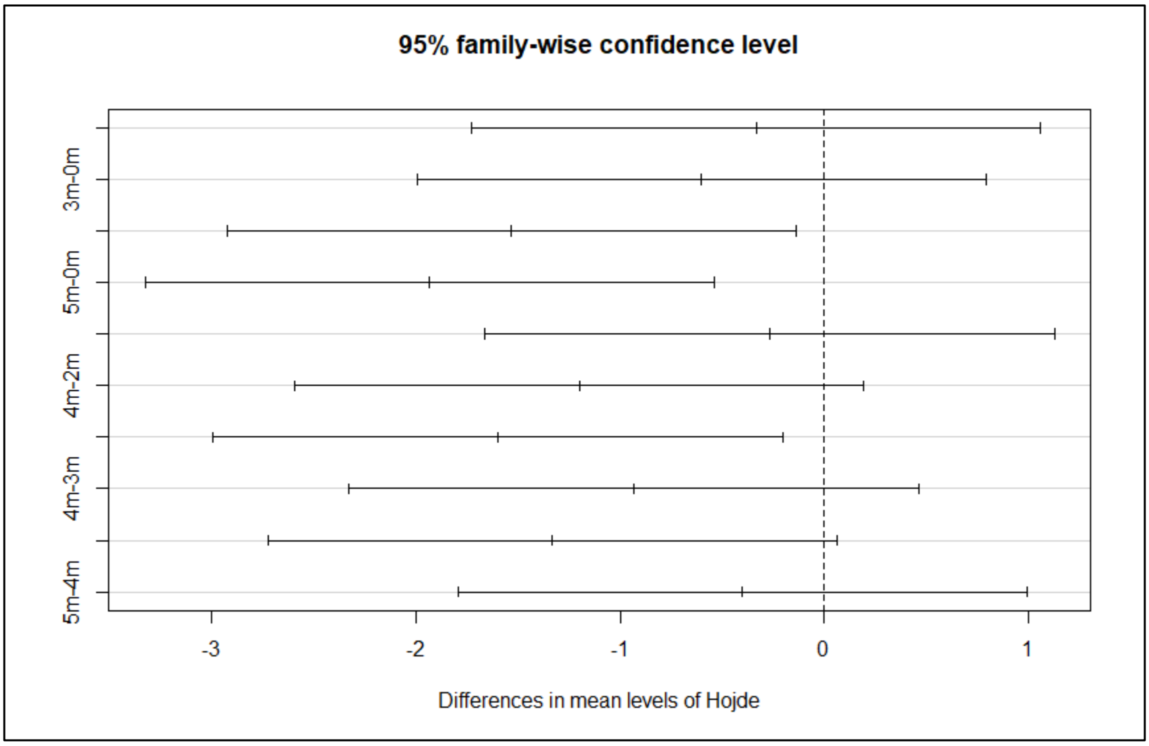

Figure S4. Results from Tukey post hoc test showing non-significant differences between ground count (0 m) and 2 m and 3 m.

Figure S5: Comparison of droppings per m^2 for 5 and 10 m spacings between the photo samples for test field 1 and test field 2 at binned intervals across the field

Registered droppings per m^2 for test **field 1** with spacings of 5 m and 10 m between the aerial photos

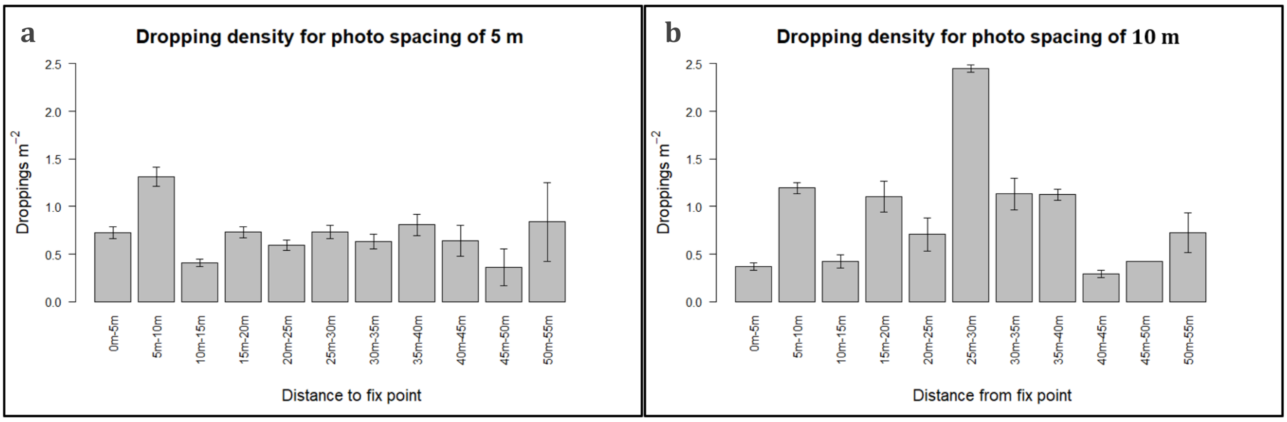

Figure S5,part 1. Difference in dropping density per m^2 for test field 1 for intervals of 5 m (0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45, 45-50 and 50-55) to the nearest fix point (water ditch). Vertical lines represent 95% confidents intervals. The total number of registered droppings were 1316 for test field 1 at 5 m thinning sample (fig. 1a) and 468 for 10 m thinning sample (fig. 1b). The area of the tested field was 2.7 hectares.

Registered droppings per m^2 for test **field 2** with spacings of 5 m and 10 m between the aerial photos

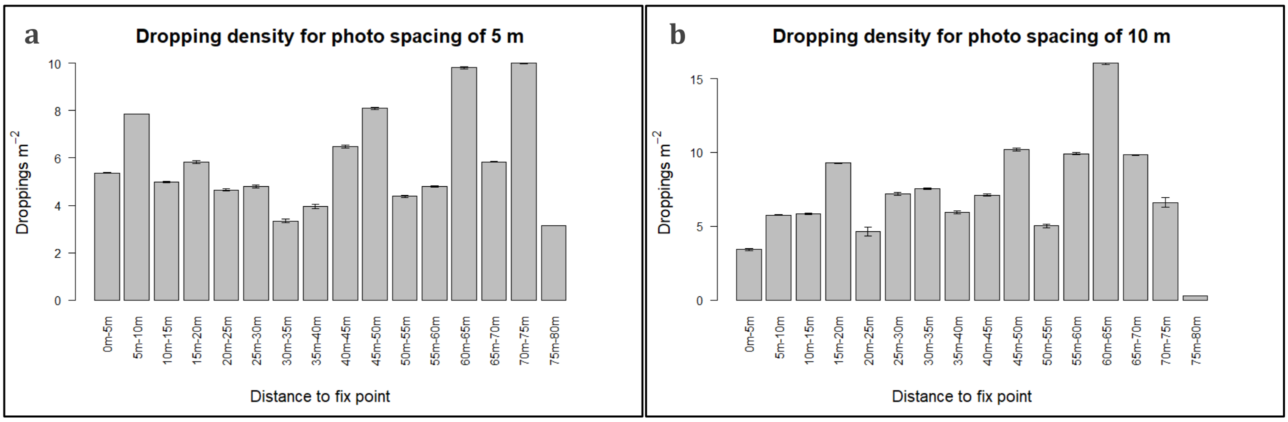

Figure S5,part 2. Difference in dropping density per m^2 for test field 2 for intervals of 5 m (0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45, 45-50, 50-55, 55-60, 60-65, 70-75 and 75-80) to the nearest fix point (water ditch). Vertical lines represent 95% confidents intervals. The total number of registered droppings were 41191 for test field 2 at 5 m thinning sample (fig. 2a) and 15468 for 10 m thinning sample (fig. 2b). The area of

Figure S6: Upper limit for thinning of aerial photos

Below are comparisons of the single photo spacings, spanning from 5 - 20 m, for test field 1 and 2. The result for both fields is an increasing variability in relative difference when all thinning samples are compared to the initial sample with 5 m spacing between the aerial photos. Notably test field 1 shows a sharper increase in relative difference and also a more viable pattern between the thinning samples than test field 2.

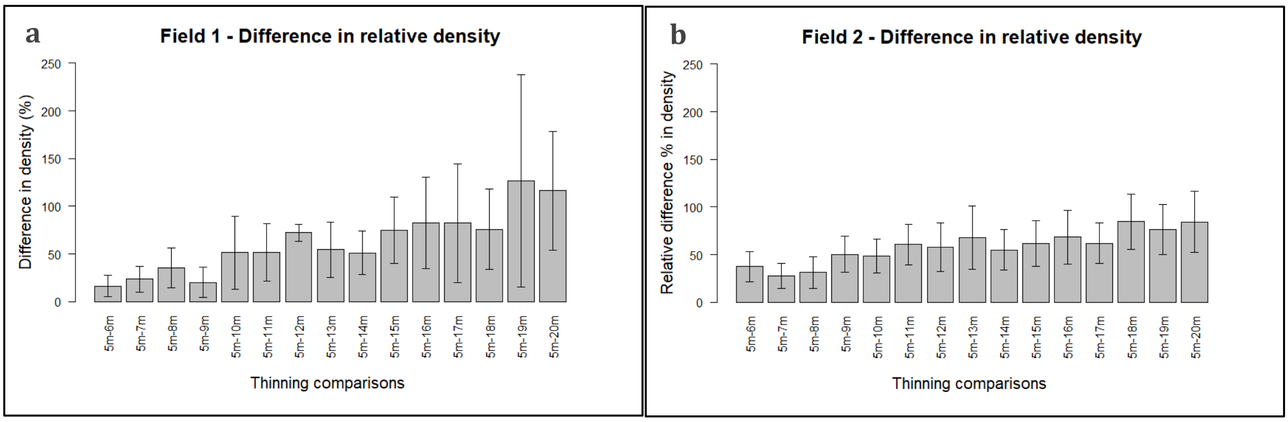

Figure S6: The relative difference in dropping density per m^2 for test field 1 (fig. 1a) and 2 (fig. 1b). Intervals of 5 m (0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45, 45-50, 50-55, 55-60, 60-65, 70-75 and 75-80) to the nearest fix point (water ditch) for each of the 16 thinning samples (5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 m) of the aerial photo data were compared to each other and an average difference was calculated. This was done for each of the different spacings starting from 5 meters spacing and ending at 20 meters between the photos. Vertical lines represent 95% confidents intervals. The total number of registered droppings were 1316 for test field 1 and 41191 for test field 2 at 5 m thinning samples. The area of the tested fields were 2.7 and 8.1 hectares for test field 1 and 2 respectively.

Figure S7: Interpolated heatmaps for all 10 surveyed fields

Below is shown individual interpolated heatmaps for all 10 surveyed fields from the 3 landscape areas.