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Mapping invasive *Lupinus polyphyllus* Lindl. in semi-natural grasslands using object-based analysis of UAV-borne images

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26 **Abstract**

27 Knowledge on the spatio-temporal distribution of invasive plant species is vital to maintain
28 biodiversity in grasslands which are threatened by the invasion of such plants and to evaluate
29 the effect of control activities conducted. Manual digitising of aerial images with field
30 verification is the standard method to create maps of the invasive *Lupinus polyphyllus* Lindl.
31 (Lupine) in semi-natural grasslands of the UNESCO biosphere reserve “Rhön”. As the
32 standard method is labour- and time-intensive, a workflow was developed to map lupine
33 coverage using an unmanned aerial vehicle (UAV)-borne remote sensing (RS) along with
34 object-based image analysis (OBIA). UAV-borne red, green, blue (R, G, B) and thermal
35 imaging, as well as photogrammetric canopy height modelling (CHM), were applied. Images
36 were segmented by unsupervised parameter optimisation into image objects representing
37 lupine plants and grass vegetation. Image objects obtained were classified using random
38 forest classification modelling based on objects’ attributes. The developed classification model
39 was employed to create lupine distribution maps of test areas and predicted data were
40 compared with manually digitised lupine coverage maps. The classification models yielded a
41 mean prediction accuracy of 89 %, and 0.78 mean kappa statistics. The maximum difference
42 in lupine area between classified and digitised lupine maps was 5 %. Moreover, the pixel-wise
43 map comparison showed that 88 % of all pixels matched between classified and digitised
44 maps. Our results indicate that lupine coverage mapping using UAV-borne RS data and OBIA
45 provides similar results as the standard manual digitising method and, thus, offers a valuable
46 tool to map invasive lupine on grasslands.

47 **Keywords:** invasive plant species; *Lupinus polyphyllus* Lindl.; unmanned aerial vehicles;
48 object-based image analysis; spatial coverage mapping; grassland

49 **1. Introduction**

50 Biological invasion is threatening to biodiversity in many ecosystems in the world. The invasion
51 by alien plant species is considered as one of the significant drivers for loss of biodiversity and
52 ecosystem functionality. The leading cause for the introduction of alien plant species is human
53 activities. After a new plant species is introduced to the ecosystem, depending on the
54 adaptation capability of the plant it obtains a naturalisation status which is the ability to self-
55 sustain without human involvement (Pyšek and Richardson 2011). At present, there are 3749
56 naturalised alien plant species in Europe, and 37.4 % out of them occur in grassland habitats
57 (Lambdon et al. 2008).

58 Processes and dynamics of invasion of plant species are complex (Courchamp et al. 2017).
59 However, knowledge on the spatial, temporal distribution of invasive plant species in a given
60 habitat is critical to understand invasion pattern (Müllerová et al. 2017), and maps showing
61 invasive plants' distribution are helpful for effective control activities. Aerial image digitising
62 verified with field survey is the standard method to create invasive plant species distribution
63 maps. Such maps are time-consuming and labour intensive to produce due to aerial image
64 acquisition, manual digitising, and field verification steps.

65 Classification of remotely sensed images to map invasive species is a well-adopted
66 technology for many invasive species in different parts of the world and various ecosystems
67 (Royimani et al. 2018). In grasslands, invasive woody (Mirik et al. 2013) and shrubby (Laliberte
68 et al. 2004; Ishii and Washitani 2013) species mapping has shown excellent results with
69 satellite and airborne image classification. Meanwhile, using an unmanned aerial vehicle
70 (UAV) borne remotely sensed (RS) imaging was increasingly applied for invasive species
71 mapping in the recent years in flood plains and coastal regions (de Sá et al. 2018; Martin et
72 al. 2018; Abeysinghe et al. 2019; Jianhui et al. 2019). Cost-effectiveness, high spatial and
73 temporal resolution and the increasing availability of various miniature sensors (e.g. RGB
74 cameras, spectral sensors, thermal cameras) are the main advantages of the UAV-borne

75 imaging compared to satellite RS data (Michez et al. 2016). Apart from the spectral or thermal
76 information, UAV-borne RS data can also provide 3D point cloud data, which can be employed
77 to derive canopy height models (CHM) for grassland canopies (Grüner et al. 2019; Wijesingha
78 et al. 2019).

79 UAV-borne RS images are very-high spatial resolution images (less than 50 cm), where one
80 object in the real world is represented by many pixels. Object-based image analysis (OBIA)
81 can better be employed when pixels are considerably smaller than the object to be identified
82 (Blaschke 2010). Several studies indicated that OBIA provides substantial advantages for
83 mapping invasive plant species based on UAV-borne RS data (Michez et al. 2016; Martin et
84 al. 2018; Abeysinghe et al. 2019). Typical OBIA employs rules derived from the object's
85 attributes to classify an object, which requires expert knowledge and limits the transferability
86 of the classification model (Belgiu et al. 2014). Contrary, machine learning classification
87 algorithms (e.g. random forest, support vector machine) have shown their capability in OBIA
88 procedures, as they do not require prior knowledge of the objects (Grippa et al. 2017).

89 *Lupinus polyphyllus* Lindl. (hereafter referred to as lupine) is on the list of the most 150
90 widespread alien plant species in Europe (Lambdon et al. 2008). The lupine plant is about 50-
91 150 cm tall and contains 1-2 cm broad leaflets. Lupine flowers are up to 80 cm long in a single
92 terminal, and they are in shades of blue, pink and white (Fremstad 2010). Lupine is native to
93 the western parts of North America and has been recorded in many habitats in Europe, such
94 as grasslands in Germany, Lithuania and at road verges as well as in ruderal areas in
95 Scandinavia (Fremstad 2010). The UNESCO biosphere reserve Rhön in Germany covers a
96 total area of 2433 km² and mainly consists of low mountain semi-natural grasslands (e.g.
97 NATURA habitat types 6520 - mountain hay meadows and 6230 - species-rich *Nardus*
98 grasslands) (Biosphärenreservat Rhön 2019). In the last few decades, lupine invaded
99 significant parts of the grasslands in the biosphere reserve and substantially changed the
100 habitat functionality mainly through the ability to fix atmospheric nitrogen, which transforms
101 the low-growing, open and species-rich grasslands into dense and productive, but species-

102 poor dominance stands (Otte and Maul 2005; Klinger et al. 2019). Individual lupine plants are
103 controlled manually at early stages of invasion to prevent a massive invasion by lupine, and
104 grassland mowing is allowed after 1st July to maintain a broad diversity of insects and ground
105 breeding birds (Biosphärenreservat Rhön 2019).

106 The knowledge of the spatial distribution of lupine in the grasslands is vital to conduct control
107 activities and to monitor their efficacy. The first lupine distribution map of the region was
108 created in 1998 using manually digitised aerial photographs at a 1:2.500 scale (Otte and Maul
109 2005). The latest map of the spatial distribution was generated in 2016 using 20 cm digital
110 ortho-mosaics from aerial photographs (Klinger et al. 2019). Those maps were useful to
111 monitor changes in the lupine distribution in the long term. The interval between the two maps
112 of eighteen years is partly due to the time and labour demanding processes involved.
113 Therefore, a repeatable, transferable methodology is needed, that produces lupine distribution
114 maps at different spatial and temporal scales to monitor the lupine distribution and to assess
115 the benefit of control activities.

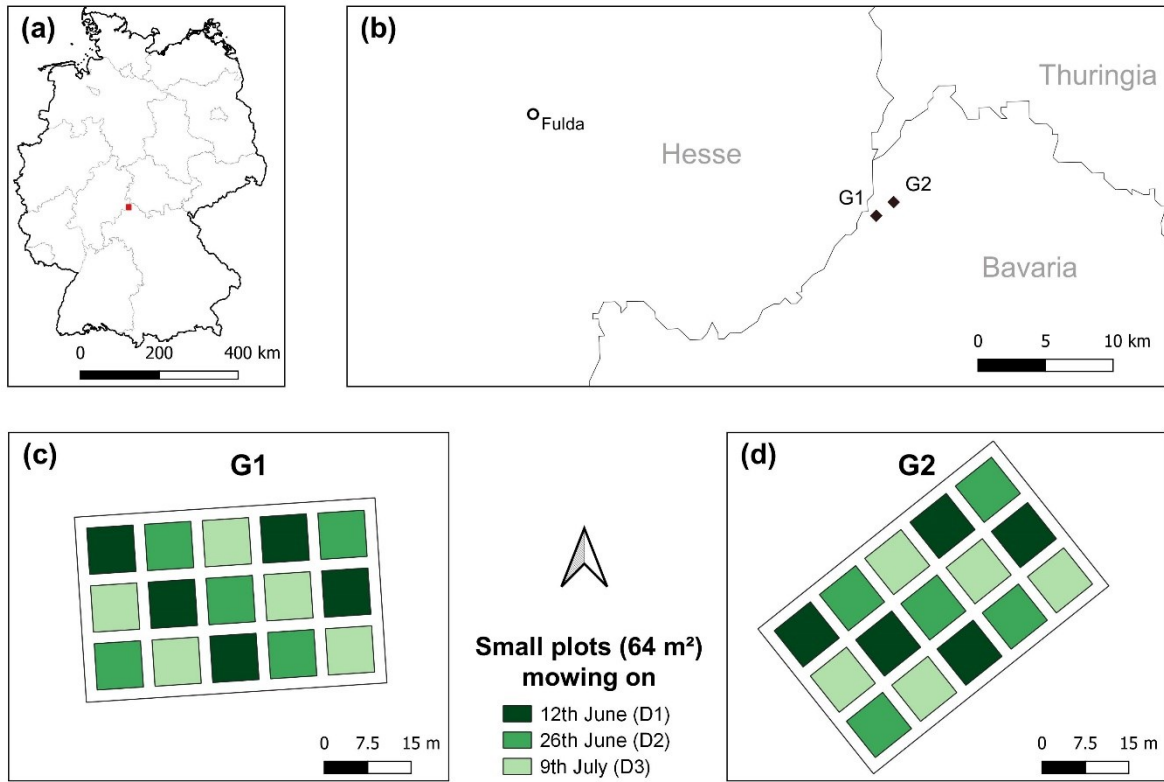
116 According to Skowronek et al., (2018), RS based mapping of the spatial distribution of Lupine
117 was not successfully implemented until now. In order to fill this gap, we propose an approach
118 to map invasive lupine in grassland, which is based on UAV-borne RS data and OBIA. We
119 hypothesise that the proposed procedure could categorise lupine and non-lupine vegetation
120 in grasslands with the same precision as the standard digitising method. This study presents
121 an operational workflow to create maps of lupine cover and compares lupine distribution maps
122 from the developed workflow with manually digitised lupine coverage maps.

123 2. Material and Methods

124 2.1. Study area

125 The study was carried out in two grassland fields UNESCO biosphere reserve Röhn in
126 Germany, which were invaded by lupine (Fig. 1a, Fig. 2). One field was classified as a former
127 mountain hay meadow (hereafter referred to as G1), and the other was an old *Nardus stricta*
128 grassland (hereafter referred to as G2). In both fields, rectangle plots of 1500 m² (50 m by 30
129 m) were chosen as study areas, and 15 small plots of 64m² (8 m by 8 m) were established
130 within a grid (Fig. 1c, 1d). Three cutting dates (12th June, 26th June, 09th July, hereafter referred
131 to as D1, D2, and D3, respectively) were randomly assigned to 5 replicated plots (Fig. 1c, 1d).
132 At each date, plots were mowed at a stubble height of 5 cm, and biomass was removed from
133 the field.

134



Administrative boundaries from GDAM data

135

136 **Fig. 1** (a) Location of the UNESCO biosphere reserve Rhön, (b) positions of the two grassland
 137 fields, and the experimental plot design of (c) G1 and (d) G2 grasslands

138



139

140 **Fig. 2** Lupine invaded grassland in the Röhn biosphere reserve.

141

142 **2.2. Data collection**

143 At each sampling date in each grassland field, UAV-borne images were acquired. A DJI-
144 Phantom IV quadcopter (DJI, China) with an inbuilt off-the-shelf camera (FC330) was
145 employed to obtain UAV-borne RGB images. The camera (FC330) captures a 12-megapixel
146 image in red (R), green (G), and blue (B) bands. The UAV was flown at 20 m flying height,
147 and it resulted in 0.09 m ground sampling distance. The UAV flight mission was designed
148 using Pix4D capture app for Android (App version 4.4.0, Pix4D, Switzerland). The UAV was
149 flown as double grid mission (two perpendicular missions), and the camera was triggered
150 automatically to capture nadir looking images based on the image overlap configuration (80
151 % both forward and side overlap). All the flight sessions were conducted between 12:00 and
152 14:00. Before each flight session, nine black and white 1m² ground control points were
153 distributed over the study area. Just after the UAV flights, the position of each ground control
154 point was measured using a Leica RTK GNSS (Leica Geosystems GmbH, Germany) with 2
155 cm 3D coordinate precision. Additional UAV-borne RGB image was taken on 16th August
156 2019, when the whole fields were mowed.

157 A FLIR Vue Pro R (FLIR Systems Incorporation, USA) thermal camera was attached to the
158 UAV parallel to the RGB camera. The camera has a 19 mm lens, and it has a spectral
159 sensitivity between 7500 - 13500 nm. With a single UAV flight, both thermal and RGB images
160 were captured simultaneously. The thermal camera captures images as a radiometric JPEG
161 which contains radiometrically calibrated temperature data. The thermal image has 640 by
162 512 pixels (FLIR 2016). The thermal camera was triggered every second throughout the whole
163 UAV mission. Before each thermal data collection, metadata related to the thermal camera
164 was collected using the FLIR UAS 2 app (App version 2.2.4, FLIR Systems Incorporation,
165 USA), such as distance to the target (20 m), relative humidity, air temperature, and emissivity
166 (0.98). All the metadata was saved in each captured image's EXIF data.

167 A total of six UAV-borne RGB and six thermal datasets were collected. Hereafter, each dataset
168 is labelled according to cutting date and grassland type (D_iG_j ; where $i = 1, 2, 3$ and $j=1, 2$). In
169 each dataset, maturity stages of grasslands were different due to mowing activities in 64 m^2
170 small plots. Maturity stage was lowest (V_0) in the D1 dataset and was the same for all 30 small
171 plots. At the 2nd cutting date (D2), 20 small plots out of 30 were covered by two weeks older
172 vegetation ($V_{2\text{weeks}}$), while 10 small plots (which were cut at D1) had vegetation which was
173 regrown for two weeks ($VR_{2\text{weeks}}$). The D3 dataset was composed of 10 plots with undisturbed
174 vegetation ($V_{4\text{weeks}}$) which was four weeks older than V_0 , 10 plots of ($VR_{2\text{weeks}}$), and further 10
175 plots with vegetation regrown for four weeks ($VR_{4\text{weeks}}$) after D1.

176

177 **2.3. Object-based image analysis**

178 **2.3.1. Canopy height model and point density**

179 Each collected dataset was processed separately, and the same procedure was applied, as
180 explained below. The UAV-borne RGB images and coordinates of ground control points were
181 processed with the Agisoft PhotoScan Professional version 1.4.4 software (Agisoft LLC,
182 Russia). The software applied structure from motion (SFM) technique to align multi-view
183 overlapping images and to build a dense 3D cloud point. The procedure of point cloud
184 generation and canopy height computation was adopted from Wijesingha et al. (2019), and
185 further details of the process can be found there.

186 The point density (PD) raster was created from the dense point cloud by binning into a raster
187 with 2cm. The PD raster contained point count under a cell area (4 cm^2). The digital terrain
188 model (reference plane) was generated using the August RGB images with a cell size raster
189 of 5 cm. The z values of 3D point cloud and the digital terrain model based on x, y locations
190 were subtracted to generate a point cloud with canopy height. The point cloud with canopy
191 height was binned into the 2 cm cell size raster, where each cell contained mean crop height
192 value and hereafter it was considered CHM raster.

193

194 **2.3.2. RGB ortho-mosaic**

195 RGB ortho-mosaic was obtained after further processing of the dense point cloud in
196 PhotoScan software. The output RGB ortho-mosaic was geo-referenced with a 1 cm spatial
197 resolution. The RGB ortho-mosaic was converted into hue (H), intensity (I), and saturation (S)
198 colour model using GRASS GIS and hereafter it was considered as HIS ortho-mosaic
199 (Gonzalez and Woods 2008; GRASS Development Team 2017).

200

201 **2.3.3. Thermal digital ortho-mosaic**

202 The single JPEG thermal image contained 8-bit digital numbers. Following workflow and
203 equations were adapted from Turner et al. (2017) to convert digital numbers to temperature
204 values. The conversion workflow was conducted with *EXIFtools* and R programming language
205 (Phil Harvey 2016; Dunnington and Harvey 2019; R Core Team 2019). A raw thermal TIFF
206 image was exported from the JPEG image. Metadata of image were extracted from the JPEG
207 EXIF header for each image. Based on the metadata and raw TIFF image values, the image
208 with temperature was computed and exported as a TIFF file. The exported TIFF image
209 contained a calibrated temperature value in degree Celsius (°C). Like RGB ortho-mosaic
210 generation, thermal ortho-mosaic with 2 cm spatial resolution was generated using calibrated
211 thermal images.

212 **2.3.4. Spectral shape index and texture images**

213 A spectral shape index (SSI) (Equation 1) based on RGB image values were computed, and
214 it showed excellent results for isolation of shadows within the vegetation (Chen et al. 2009).
215 Moreover, two texture features (second-order statistics texture namely angular second
216 moment (ASM) - uniformity, and inverse difference moment (IDM) - homogeneity) (Haralick
217 1979) from both intensity image and thermal image were computed.

$$SSI = |R + B - 2\check{G}| \quad (1)$$

218 where R, G, and B are red, green, and blue values respectively.

219 **2.3.5. Segmentation**

220 Segmentation and classification are the two main steps in OBIA (Silver et al. 2019). The
 221 segmentation is the first step and by definition "it divides an image or any raster or point data
 222 into spatially continuous, disjoint and homogeneous regions, referred to as segments or image
 223 objects" (Blaschke et al. 2014). According to Espindola et al., (2006), the quality of
 224 segmentation depends on the balance between intersegment homogeneity (the similarity
 225 between segments) and intersegment heterogeneity (the difference between segments).

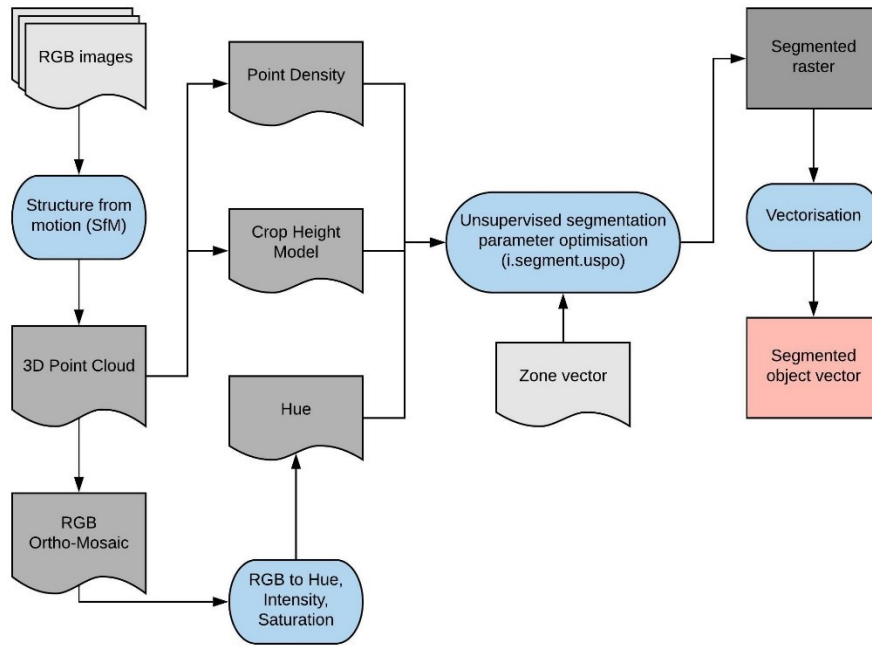
226 Variance and spatial autocorrelation (Moran's I) between segments are utilised as measures
 227 to evaluate intersegment homogeneity and heterogeneity respectively. A low variance leads
 228 to over-segmentation of images, as very similar pixels are contained in each segment which
 229 divides one real-world object into many segments. In contrast, a low spatial autocorrelation
 230 between segments can increase the variance, and it causes under-segmentation, which gives
 231 one large segment that covers many different real-world objects. The segmentation threshold
 232 (also referred to as scale) can control the balance between intersegment variance and spatial
 233 autocorrelation. Therefore, finding the optimum threshold is essential to produce segments
 234 which are matching to the real-world objects (Espindola et al. 2006).

235 Johnson et al. (2015) established an F measure to identify the quality of the segmentation
 236 result for a given threshold value. The F measure is based on variance and spatial
 237 autocorrelation and calculated using Equation 2 (Johnson et al. 2015). A weight value (alpha)
 238 must be defined in the F measure, with 0.5 is half weighting, and 2 is double weighting. Like
 239 the normalise sum measure, the higher the F measure, the higher the quality of the
 240 segmentation.

$$F = (1 + \alpha^2) \left(\frac{MI_{norm} \check{V}_{norm}}{\alpha^2 \check{MI}_{norm} + V_{norm}} \right) \quad (2)$$

241 here MI_{norm} is the normalised Moran's I value, V_{norm} is the normalised variance value, α is the
242 alpha weight, and F is the F measure.

243 Espindola et al., (2006) introduced the Unsupervised Parameter Optimisation (USPO)
244 procedure to identify the optimum threshold value for the given image from a range of
245 threshold values based on one of the quality measures mentioned above. The USPO
246 procedure was implemented as an add-on tool called *i.segment.uspo* in GRASS GIS software
247 (Lennert and GRASS Development Team 2019a). The CHM raster, PD raster and hue image
248 from HIS ortho-mosaic were used in the segmentation process (Fig. 3). According to
249 Georganos et al. (2018), finding the optimum threshold values for different local image regions
250 gives superior results compared to the use of a single threshold for the whole image. Hence,
251 the image was divided into sixteen small zones (15 zones overlapping with the 64 m² plots for
252 each study plot and one zone for the paths between the plots). Specific local thresholds
253 (ranging from 0.01 to 0.15) was determined for each region based on the F measure. The
254 alpha value in the F measure calculation was kept at 0.5. Python *Jupyter Notebook* codes
255 from Grippa (2018) were adopted and modified according to this study for automatizing the
256 segmentation process using *i.segment.uspo* for each zone. The segmentation procedure was
257 applied separately for each study plot and sampling date. A total of six different segmented
258 raster were created according to six datasets.



259

260 **Fig. 3** Flow diagram of the segmentation with *i.segment.uspo* and attribute calculation using
 261 GRASS GIS

262

263 **2.3.6. Attribute calculation for segmented image objects**

264 The segmented raster was vectorised, and each segmented object was created as a polygon.
 265 Four geometric attributes (area (A), perimeter (P), fractional dimension (FD) (Equation 3), and
 266 circle compactness (CC) (Equation 4)) for the segmented objects were calculated. Based on
 267 all raster data (RGB image, HIS image, CHM raster, PD raster, thermal image, SSI image,
 268 and texture raster), the mean and standard deviation values for each polygon was computed
 269 as image-based attributes. Attribute calculation was done using *i.segment.stats* add-on in
 270 GRASS GIS (Lennert and GRASS Development Team 2019b). In total, 32 attributes (4
 271 geometric and 28 image-based) were generated (Table 1).

$$FD = 2 \sqrt{\frac{\log P}{\log(A + 0.001)}} \quad (3)$$

$$CC = \frac{P}{2 \sqrt{TA}} \quad (4)$$

272

273 Table 1: Description of the calculated object's attributes

ID	Attribute	Description
1	Area	Area of the object
2	Perimeter	Perimeter of the object
3	FD	Fractional dimension of the object
4	CC	Circle compactness of the object
5	Mean R	Mean red image value of the object
6	Mean G	Mean green image value of the object
7	Mean B	Mean blue image value of the object
8	Mean hue	Mean hue image value of the object
9	Mean intensity	Mean intensity image value of the object
10	Mean saturation	Mean saturation image value of the object
11	Mean intensity ASM	Mean intensity ASM texture image value of the object
12	Mean intensity IDM	Mean intensity IDM texture image value of the object
13	Mean SSI	Mean spherical shape index image value of the object
14	Mean temperature	Mean temperature image value of the object
15	Mean thermal ASM	Mean thermal ASM texture image value of the object
16	Mean thermal IDM	Mean thermal IDM texture image value of the object
17	Mean CHM	Mean canopy height model value of the object
18	Mean PD	Mean point density value of the object
19	SD R	Standard deviation of red image value of the object
20	SD G	Standard deviation of green image value of the object
21	SD B	Standard deviation of blue image value of the object
22	SD hue	Standard deviation of hue image value of the object
23	SD intensity	Standard deviation of intensity image value of the object
24	SD saturation	Standard deviation of saturation image value of the object
25	SD intensity ASM	Standard deviation of intensity ASM texture image value of the object
26	SD intensity IDM	Standard deviation of intensity IDM texture image value of the object
27	SD SSI	Standard deviation of spherical shape index image value of the object
28	SD temperature	Standard deviation of temperature image value of the object
29	SD thermal ASM	Standard deviation of thermal ASM texture image value of the object
30	SD thermal IDM	Standard deviation of thermal IDM texture image value of the object
31	SD CHM	Standard deviation of canopy height model value of the object
32	SD PD	Standard deviation of point density value of the object

274

275 **2.3.7. Classification model**

276 Ten percent of the segmented objects (3698 out of a total of 81704 objects) were manually
 277 labelled as either lupine (L) or non-lupine (NL) based on visual observation using the RGB

278 ortho-mosaics. In each dataset, the number of L and NL labels were very similar (L = 1892
279 and NL = 1806), and labelled objects were spatially randomised. The labelled objects with
280 attributes were utilised to develop a supervised classification model.

281 Classification model training and testing were conducted using R statistical software (R Core
282 Team 2019). The random forest (RF) machine learning classification algorithm was employed
283 to build a classification model using the *mlr* package in R software (Bischl et al. 2016). The
284 RF has proven its efficiency for image object classification using objects' attribute data (Belgiu
285 and Drăgu 2016). The RF algorithm utilises both decision trees and bagging (Breiman 2001).
286 The decision trees are created from a subset of the training samples with replacement (known
287 as bagging). Based on the average outcome from the decision trees, the sample is assigned
288 to a majority class (Belgiu and Drăgu 2016).

289 A total of six RF classification models were built, and in each model, five datasets were
290 employed to train the model, while the remaining dataset was used to test the model (Table
291 2). All the attributes (32) were employed as an input of the model along with objects' labels.
292 Two hyperparameters, namely *mtry* (number of selected variables in each split) and *node size*
293 (number of observations in a terminal node) (Probst et al. 2019) were tuned in the model
294 training phase using random search. The model was trained with repeated spatial cross-
295 validation resampling (five-folds and two repeats) to classify objects. In spatial cross-
296 validation, the resampling is based on the location of the observations to reduce the effect of
297 spatial autocorrelation for model accuracy, where it is crucial for spatial-temporal context
298 (Brenning 2012). The location was based on the centroid of the objects. The trained model
299 employed to predict objects' labels of the holdout dataset. According to predicted labels and
300 actual labels, the model performance was evaluated by calculating overall accuracy (OA),
301 true-positive-rate (TPR), false-positive-rate (FPR), and Kappa (K) values (Equation 5, 6, 7,
302 and 8 respectively).

303

304 Table 2: Details of the training and testing datasets for different classification models

Model Name	Datasets for training	Dataset for testing
M11	D ₁ G ₂ , D ₂ G ₁ , D ₂ G ₂ , D ₃ G ₁ , D ₃ G ₂	D ₁ G ₁
M12	D ₁ G ₁ , D ₂ G ₁ , D ₂ G ₂ , D ₃ G ₁ , D ₃ G ₂	D ₁ G ₂
M21	D ₁ G ₁ , D ₁ G ₂ , D ₂ G ₂ , D ₃ G ₁ , D ₃ G ₂	D ₂ G ₁
M22	D ₁ G ₁ , D ₁ G ₂ , D ₂ G ₁ , D ₃ G ₁ , D ₃ G ₂	D ₂ G ₂
M31	D ₁ G ₁ , D ₁ G ₂ , D ₂ G ₁ , D ₂ G ₂ , D ₃ G ₂	D ₃ G ₁
M32	D ₁ G ₁ , D ₁ G ₂ , D ₂ G ₁ , D ₂ G ₂ , D ₃ G ₁	D ₃ G ₂

305

$$OA = \frac{TP + TN}{TP + FN + FP + TN} \quad (5)$$

$$TPR = \frac{TP}{TP + FN} \quad (6)$$

$$FPR = \frac{FP}{FP + TN} \quad (7)$$

$$K = \frac{\text{Observed agreement} - \text{Expected agreement}}{1 - \text{Expected agreement}} \quad (8)$$

306 Where TP is true positives, TN is true negative, FP is false-positive, and FN is false-negative.

307

308 2.4. Lupine coverage mapping

309 A single RF classification model (M_{all}) was trained using all labelled objects from the six
 310 datasets. Based on predicted labels from M_{all} , a lupine coverage map was generated
 311 (hereafter referred to as classification-based lupine coverage map).

312 A reference lupine coverage map for each dataset was created by digitising each RGB ortho-
 313 mosaic and was compared to the lupine area from the classification-based lupine coverage
 314 map. A relative number of no-difference pixels from two maps was computed as a measure
 315 for map accuracy (MA) (Equation 9). Additionally, the pixel-wise correlation coefficient (PCC)
 316 was calculated. Each 64 m² plot was divided into four equal areas of 16m² each, and the

317 relationship between relative digitised lupine area (LA) and MA of subdivided plots was
318 analysed to understand the MA at different levels of LA.

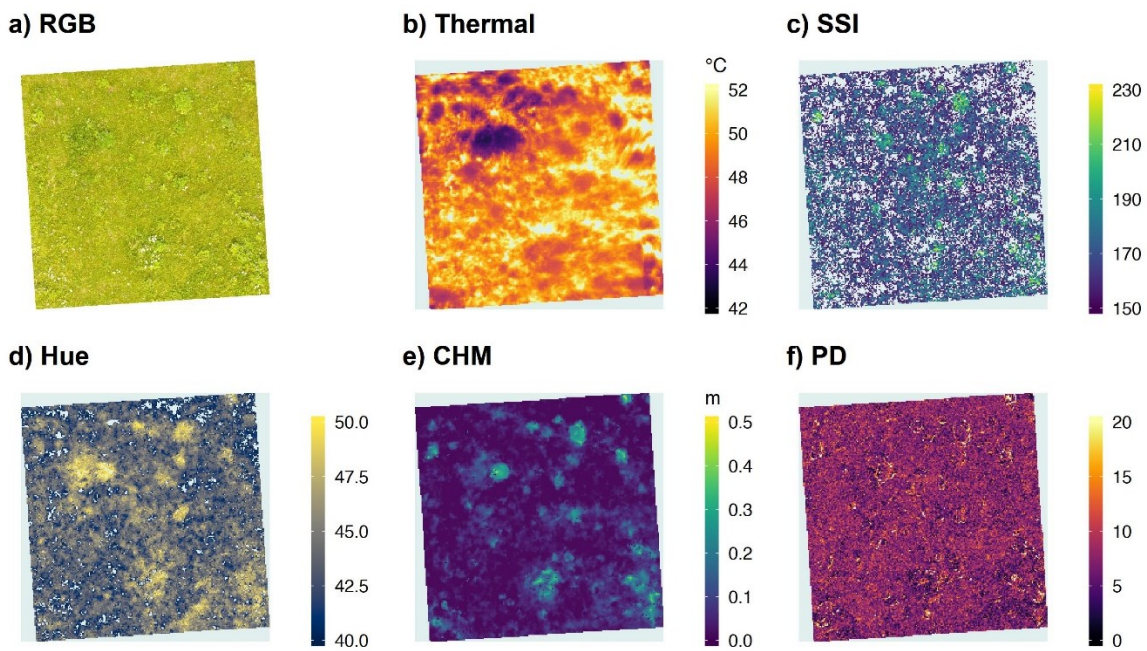
$$MA = \frac{\text{Number of equally categorised pixels in the two maps}}{\text{Total number of pixels}} \times 100 \quad (9)$$

319

320 **3. Results**

321 **3.1. Image segmentation**

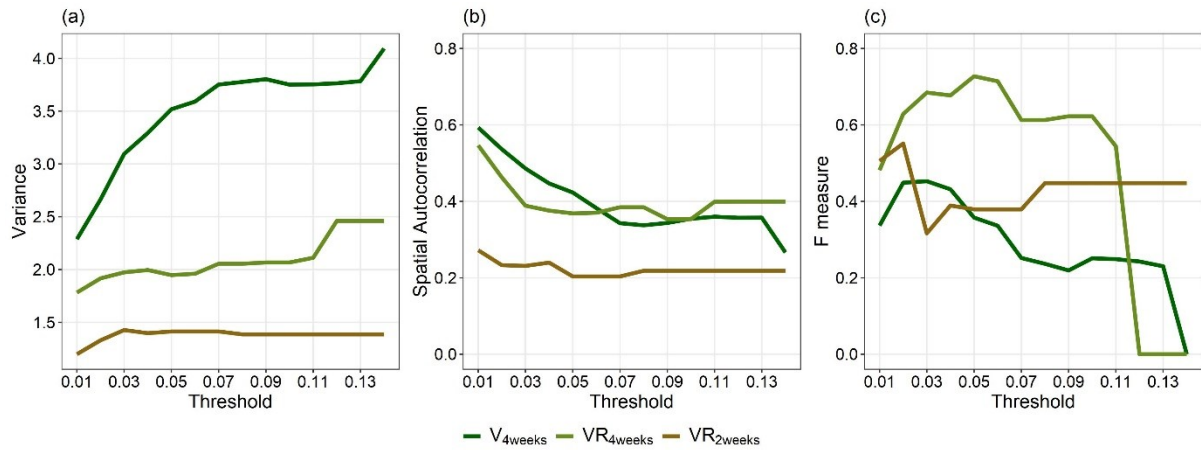
322 Ortho-mosaics from RGB and thermal camera images were created in this study and SSI, and
323 hue images were computed from the RGB ortho-mosaic. RGB images were processed with
324 SFM technique to generate CHM raster and PD raster. Exemplary images and raster from D1
325 of G1 are shown in Fig. 4.



326

327 **Fig. 4** Exemplary images for D1G1 (Field G1, 12th June) dataset (a) RGB digital ortho-mosaic,
328 (b) Thermal digital ortho-mosaic, (c) spectral shape index (SSI) image, (d) hue image, (e)
329 canopy height model (CHM) raster, and (f) point density (PD) raster

330 The CHM raster, PD raster, and hue image were utilised to create image objects. The optimum
331 threshold values for different image regions were determined using USPO. As shown in Fig.
332 5, three image regions with different vegetation maturity obtained distinct optimum threshold
333 values. Example segmented image is shown in the Appendix (Fig. 9).



334

335 **Fig. 5** Course of (a) variance, (b) spatial autocorrelation, and (c) F measure values for different
 336 threshold values in three different image regions where VR_{4weeks}: regrown vegetation 4 weeks
 337 after mowing, VR_{2weeks}: regrown vegetation 2 weeks after mowing, and V_{4weeks}: vegetation four
 338 weeks older than 12th June vegetation

339

340 3.2. Classification model training and testing

341 Six classification models were trained while holding out one dataset at each time. The model
 342 results are summarised in Table 3. Based on the all performance measures in model testing
 343 phase, model M12 (model tested with D₁G₂ data) obtained the lowest performances (OA =
 344 78.2 %, K = 0.55) and model M32 (model tested with D₃G₂ data) achieved the highest values
 345 (OA = 97.2 %, K = 0.94). Although model M12 accurately classified all lupine objects (100 %
 346 TPR), it also categorised nearly half of the non-lupine objects as lupine objects (47.3 % FPR).
 347 Additionally, models that tested with D1 data (M11 and M12) obtained slightly lower
 348 performances compared to other models.

349 Table 3: Classification model results (L: lupine, NL: non-lupine, TA: training accuracy, OA:
 350 overall accuracy, K: Kappa statistics, TPR: true-positive rate, FNR: false-negative rate)

Model	Training	Testing				
	No. of objects	No. of objects	OA (%)	TPR (%)	FPR (%)	K
M11	L = 1581; NL = 1545	L = 311; NL = 261	83.2	76.8	9.2	0.67
M12	L = 1394; NL = 1381	L = 498; NL = 425	78.2	100.0	47.3	0.55
M21	L = 1578; NL = 1429	L = 314; NL = 377	90.6	84.1	4.0	0.81
M22	L = 1701; NL = 1638	L = 191; NL = 168	96.4	95.8	3.0	0.93

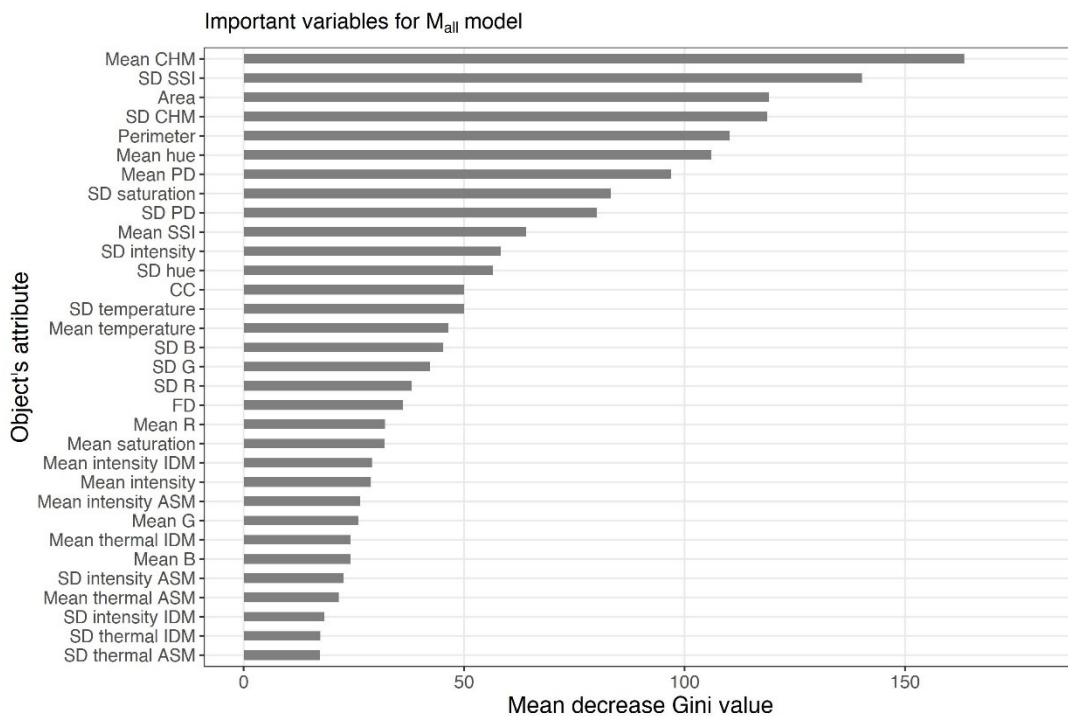
M31	L = 1530; NL = 1405	L = 362; NL = 401	90.1	88.4	6.7	0.82
M32	L = 1676; NL = 1632	L = 216; NL = 174	97.2	96.7	2.3	0.94

351

352 3.3. Final classification model and important attributes

353 After testing six classification models with the different spatial-temporal dataset, the complete
 354 classification model (M_{all}) was trained using all available data (3698 objects) with spatial cross-
 355 validation. The M_{all} model achieved 94.2 % training accuracy.

356 The importance of the objects' attributes to the M_{all} classification model was assessed based
 357 on the mean decrease Gini value (Fig. 6). It is based on "the total decrease in node impurities
 358 from splitting on the variable, averaged over all trees" (Liaw and Wiener 2002). The six most
 359 important variable of the model were *Mean CHM*, *SD SSI*, *Area*, *SD CHM*, *Perimeter*, and
 360 *mean hue* attribute values. Attributes related to texture features were the least essential
 361 prediction variables to the M_{all} model.



362

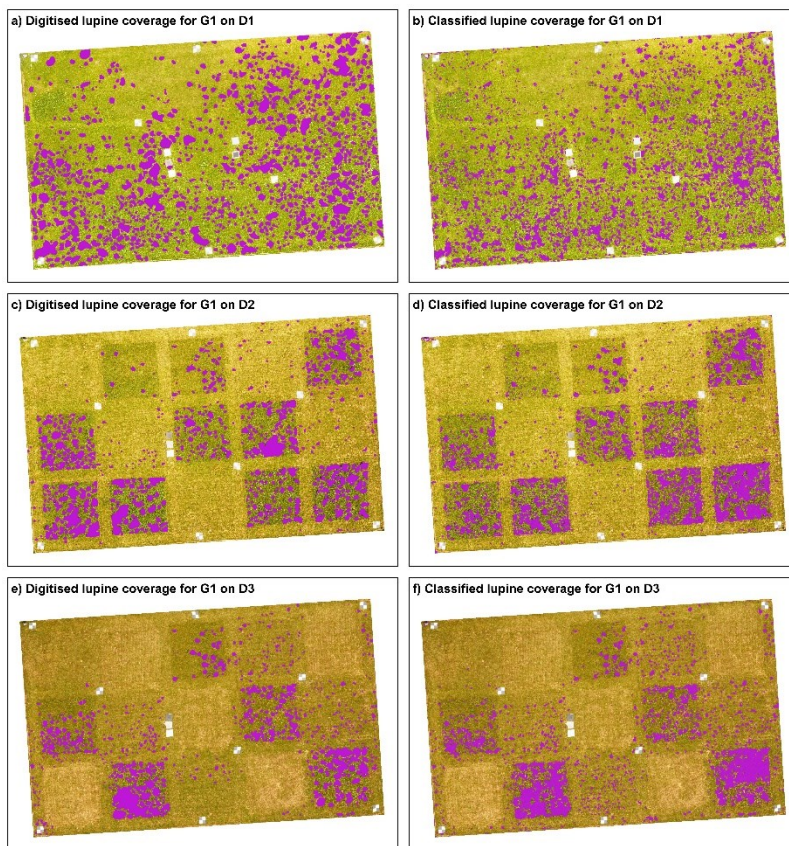
363 **Fig. 6** Important object's attributes for the M_{all} classification model (complete model) based on
 364 mean decrease Gini values

365

366 3.4. Lupine coverage maps

367 Based on visual observation between digitised lupine map and classified lupine map, both
368 maps showed similar visual representation. Fig. 7 illustrates lupine coverage maps from both
369 digitising and classification for three sampling dates (D1, D2, D3) in G1 field. However, the
370 area-based comparison showed maximum $\pm 5\%$ of the change in total lupine coverage (Table
371 4).

372



373

374 **Fig. 7** Lupine coverage map of the G1 field with a, c, e, showing manually digitised lupine
375 cover (purple) at D1 (12th June), D2 (26th June), and D3 (9th July) and b, d, f, showing lupine
376 cover classified by UAV-borne RS data and OBIA

377

378

379 The classification based lupine coverage was assessed against reference lupine coverage
 380 map using comparing pixels in two raster maps. From comparison results, map accuracy
 381 relative to the reference map and CC was computed (Table 4). According to raster comparison
 382 results, D1 dataset obtained the lowest MA (80.4 %, 80.9 %) and PCC (0.40, 0.50) values in
 383 G1 and G2 fields respectively. The MA and CC values tended to increase with reducing lupine
 384 coverage. However, comparison results for G2 dataset always indicated slightly better results
 385 than G1.

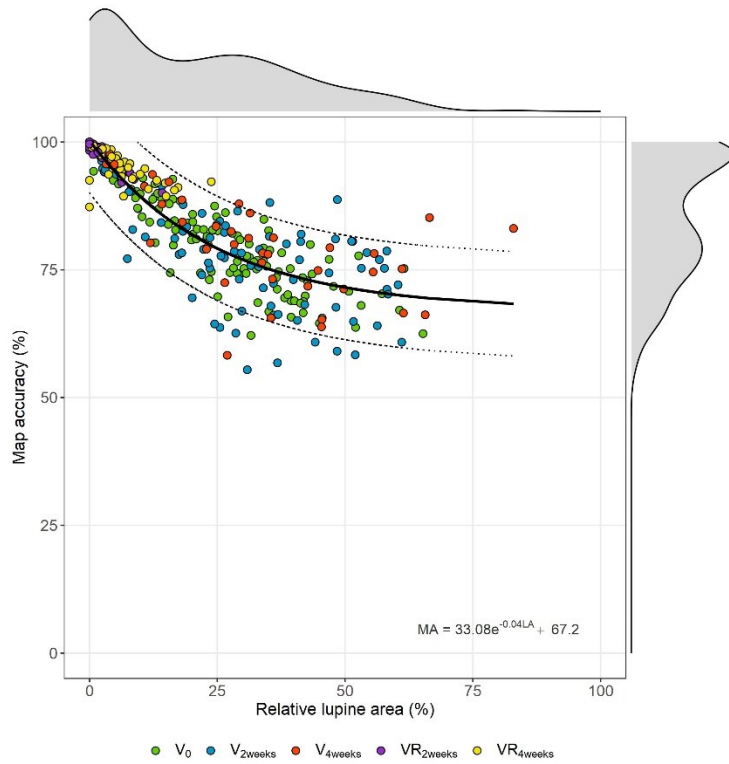
386

387 Table 4: Pixel-based comparison between manually digitised and classified lupine coverage.
 388 (LA: lupine area, MA: map accuracy, PCC: pixel-wise correlation coefficient)

Date	Field	LA	Relative LA difference	MA	PCC
D1	G1	294 m ²	-5 %	80.4 %	0.40
	G2	443 m ²	+3 %	80.9 %	0.50
D2	G1	237 m ²	+1 %	88.7 %	0.52
	G2	308 m ²	+3 %	89.0 %	0.61
D3	G1	188 m ²	+2 %	93.1 %	0.63
	G2	181 m ²	+2 %	93.8 %	0.68

389

390 Relationship between the relative LA and MA indicated a negative exponential trend (Fig. 8).
 391 The correlation coefficient between relative LA and MA was -0.88, and trend line had 0.80
 392 goodness of fit. Regardless of the vegetation maturity, the explained relationship was valid.
 393 Until LA reached 25 %, it showed a strong relationship with MA, but over 25 % LA the MA
 394 values were scattered around the regression curve.



395

396 **Fig. 8** The relationship between relative lupine area (LA) from manual digitising and map
 397 accuracy (MA) based on the generalised model, comprising undisturbed/not mowed
 398 vegetation (V_0 , V_{2weeks} , V_{4weeks}), and regrown vegetation after mowing (VR_{2weeks} , VR_{4weeks})

399

400 4. Discussion

401 Invasion by lupine endangers biodiversity and ecosystem functionality (Otte and Maul 2005;
402 Klinger et al. 2019). The spatial and temporal distribution of lupine is essential to understand
403 the invasive pattern, to plan appropriate management strategies and to monitor the impact of
404 control actions. While RS was utilised to map several invasive plant species (e.g. *Impatiens*
405 *glandulifera*, *Spartina anglica*, *Solidago canadensis*), invasion patterns of lupine were not
406 examined until now (Skowronek et al. 2018). This study aimed to develop an operational
407 workflow to map the spatial distribution of invasive lupine in grasslands using UAV-borne
408 imageries and OBIA.

409 OBIA has shown its' effectiveness to work with very high-resolution (< 1 m spatial resolution)
410 images, where several pixels represent one object rather than classifying each pixel
411 separately. While OBIA allowed taking advantage of RGB images only, a pixel-based
412 classification approach would have demanded spectral signatures. Segmentation is the critical
413 step in the OBIA. The first step of the proposed workflow was to segment collected UAV-borne
414 images into image objects that represent either lupine or non-lupine (i.e. mainly grass) plants.
415 USPO based area-specific threshold values benefitted for obtaining good object delineation
416 (**Error! Reference source not found.**). However, USPO for a multitude of image areas leads
417 to an increased computational time corresponding to the size of the areas and the spatial
418 resolution of the images (Georganos et al. 2018).

419 Apart from optimal threshold identification, different combinations of various raster types were
420 tested (data not shown). Visual assessment of the segments obtained suggested that the
421 combined raster with CHM, PD and hue data provided the best segmentation results. This is
422 comprehensible, as the canopy height of lupine plants is usually taller than the surrounding
423 grass vegetation (Otte and Maul 2005), also resulting in higher point densities at the edges of
424 the lupine plant than in the plants' centres. Therefore, CHM and PD raster data significantly
425 contributed to the delineation of objects and the contour like pattern can be seen from

426 segmented raster (Appendix Fig. 9). CHM data has been utilised recently as classification
427 variable for invasive species mapping (Jones et al. 2011; Lehmann et al. 2017), but this is the
428 first study where CHM data was employed to delineate objects in invasive species mapping.
429 Additionally, hue data derived from RGB images characterised the degree of pureness of the
430 colour compared to the primary colours (Gonzalez and Woods, 2008) also assisted in defining
431 object boundaries.

432 Random forest classification models with 32 attributes as predictors were trained and tested
433 based on different datasets. The model M12 obtained the highest TPR but got the lowest FPR
434 and tended to over-classify non-lupine objects as lupine objects. As the M12 model was tested
435 with datasets containing only young lupine plants, small objects that were not lupine may have
436 been overestimated. This may also be true for the M11 model, which had a similarly low
437 accuracy compared to the other models. Overall, the performance of the six models showed
438 high model stability and robustness across time and space, which indicates that the models
439 could be transferred easily to other grassland sites of varying maturity. As demonstrated with
440 previous studies (Belgiu and Drăgu 2016), our results confirmed that RF modelling creates
441 robust algorithms to use object classification in OBIA for vegetation mapping.

442 Several attributes related to plant structure or architecture as well as colour were essential
443 predictors in the M_{all} model. The height difference between lupine plants and grass vegetation
444 contributed to the classification of segmented objects. It points at a prominent advantage of
445 UAV-borne RS, which allows the separation of two plant types by CHM attributes. This was
446 also proven by other studies that utilised CHM from UAV-borne RS data to map invasive
447 species mapping (i.e. *Phragmites australis* in estuaries by Abeysinghe et al. (2019) and
448 *Fallopia* spp. in floodplains by Martin et al. (2018)).

449 Segment's area and perimeter were further vital geometric features in the final classification
450 model, whereas fractional dimensions and circle compactness were not useful. A closer look
451 at the segmented objects shows that area (average values were 0.04 m² and 0.17 m² for L
452 and NL objects respectively) and perimeter (average values were 1.6 m and 3.5 m for L and

453 NL objects respectively) of lupine objects were substantially smaller compared to non-lupine
454 objects, irrespective of the lupine coverage (Appendix Fig. 10). The automated process
455 segmented lupine objects always in relatively small areas even when large parts of the area
456 were covered by lupine. Our findings confirm results from other studies, where area and
457 perimeter were essential variables in discrimination models, e.g. species mapping in arid
458 areas as demonstrated by Silver et al. (2019).

459 To reduce the computation complexity, only two texture parameters (angular second moment,
460 inverse difference moment) were computed out of many existing parameters. Surprisingly, all
461 four texture attributes (intensity-based and thermal-based) were ineffective in our study.
462 Previous studies (Chabot et al., 2018; Silver et al., 2019) with OBIA have proven that textural
463 information was useful. However, they utilised many more texture attributes than employed in
464 our study. Hence, the accuracy of our models might be increased by including further texture
465 parameters.

466 Corresponding to the intense green colour of lupine leaves and pronounced red and blue
467 shades of flowers, SSI values computed from RGB intensities indicated higher values in leafy
468 areas and lower values in regions, where flowering lupines dominated. Consequently, an
469 increased cover of lupine plants at different maturity stages resulted in increased standard
470 deviations of SSI, due to a broader distribution of the SSI values (Appendix Fig. 10). This may
471 explain why the variation of standard deviation values among objects supported the
472 categorisation of lupine and non-lupine objects.

473 As lupine plants contain higher water contents compared to grasses (Hensgen and
474 Wachendorf 2016), lupine containing areas in thermal images showed lower temperatures
475 compared to the surrounding grass area (**Error! Reference source not found.b**).
476 Additionally, the bushy structure of lupine plants creates shaded areas in the surrounding,
477 which may have further decreased temperature. Surprisingly, temperature-related attributes
478 (temperature or texture attributes from thermal image) did not become significant predictors
479 in the classification models. Evidently, other predictors were of superior relevance than the

480 temperature attributes. However, this leads to reduced costs for sensors and platforms as
481 well as model complexity and computing time.

482 As relative LA increased, the MA of the lupine coverage maps that generated from our
483 workflow decreased (**Error! Reference source not found.**). The negative relationship was
484 valid for both undisturbed vegetation of different maturity and regrown vegetation after
485 mowing. With an increasing lupine area, the classification procedure tends to over-estimate
486 lupine coverage due to difficulty to separate lupine and grass vegetation. In general, early
487 detection of invasive plant species and rapid action is critical to control invasive species (Cock
488 and Wittenberg 2001). Similarly, for lupine management activities, ecologists prefer to act in
489 regions with lower lupine coverage, as at this stage of invasion, eradication and containment
490 are easier than high lupine coverage regions. Since maps with lower lupine coverage were
491 accurate, ecologists can identify regions with relatively small lupine coverage and precisely
492 locate single lupine plants for eradication.

493 Though it could be shown that the proposed method performed as well as the standard
494 digitising method, it may be criticised that vegetation mapping based on UAV-borne RS data
495 is challenging to scale up (e.g. Chabot et al., 2018). In this study, one UAV flight took 20
496 minutes (including ground preparation and flight time) to collect data of approximately 0.4
497 hectares (without thermal sensor). The conduction of additional flight sessions, as well as
498 expected advance in sensor and platform technology, may lead to an increased data
499 acquisition area in the future. The proposed method can be considered cost-efficient, as it only
500 requires a standard UAV-mounted RGB camera, and as most of the utilised software is free
501 and open-source (GRASS GIS, R, QGIS), except the Agisoft PhotoScan software, which could
502 be replaced with available free software (e.g. open drone map).

503 Our proposed classification approach can easily be applied in other comparable
504 environments, as the model was trained with heterogeneous datasets from commonly
505 occurring grassland vegetation at different stages of maturity. The spatial lupine coverage
506 maps that were created can be utilised i) to identify the distribution of lupine in grasslands, ii)

507 to estimate the size and degree of lupine invasion by comparing maps generated in different
508 years, and iii) to evaluate the effectiveness of lupine control. As suggested by Kattenborn et
509 al., (2019), UAV-borne lupine coverage maps can further be employed for the creation of field
510 samples to train and test satellite image-based models for invasive lupine mapping in larger
511 areas.

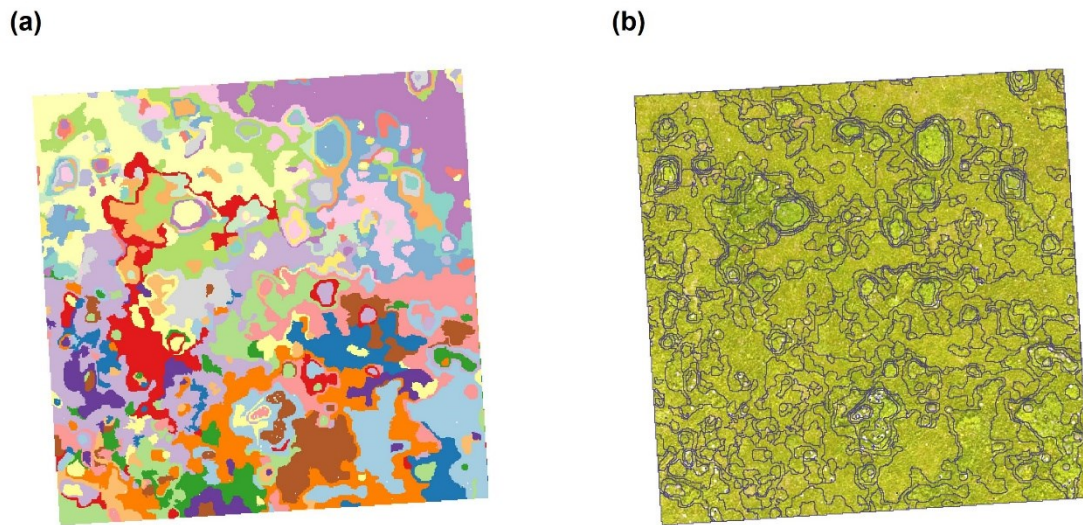
512 **5. Conclusion**

513 Gaining knowledge on the spatio-temporal distribution of lupine is vital to maintain biodiversity
514 in grasslands which are threatened by the invasion of this plant. We successfully developed a
515 workflow that can accurately map lupine coverage in a grassland using UAV-borne RS and
516 OBIA. In our proposed workflow, we developed a robust RF classification model that can
517 classify lupine and non-lupine image objects. The resulting maps showed a ± 5 % discrepancy
518 in the lupine area compared to the standard digitising method. Moreover, the classification
519 model can be transferred to other regions, and thereby overcomes limitations of the standard
520 way of lupine mapping. Finally, the developed procedure can be adopted for mapping other
521 invasive species.

522

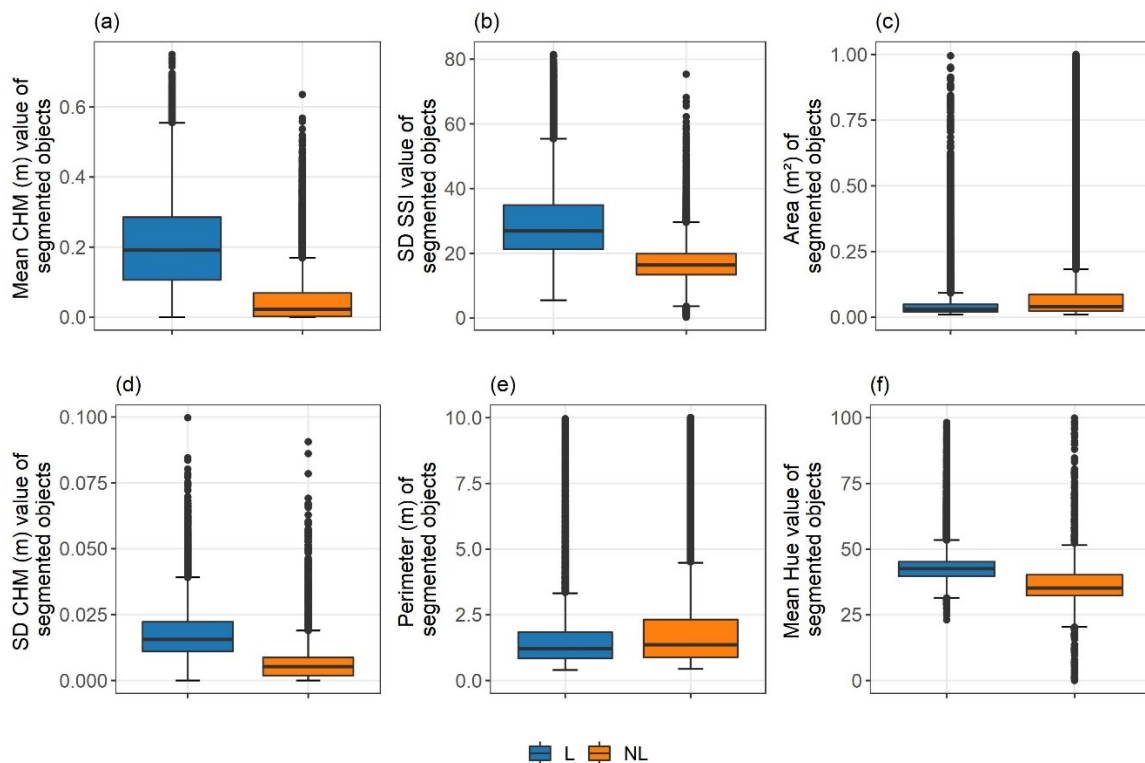
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527 helping with image digitising. We are also grateful to the government of Bavaria for permission
528 to conduct our measurements in a nature conservation area.



530

531 **Fig. 9** Subset of the (a) segmented object raster (unique colour represents a single segmented
 532 object and colours are repeated), and (b) vectorised segmented object overlay with RGB
 533 image for G₁D₁ (Field G1, 12th June) dataset



534

535 **Fig. 10** Distribution of the values of the most six significant predictors in the classification
 536 model for Lupine (L), and non-Lupine (NL) category. (a) mean canopy height model values,
 537 (b) standard deviation values of spectral shape index, (c) area values, (d) standard deviation
 538 values of canopy height model, (e) perimeter values, and (f) mean hue values

539

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