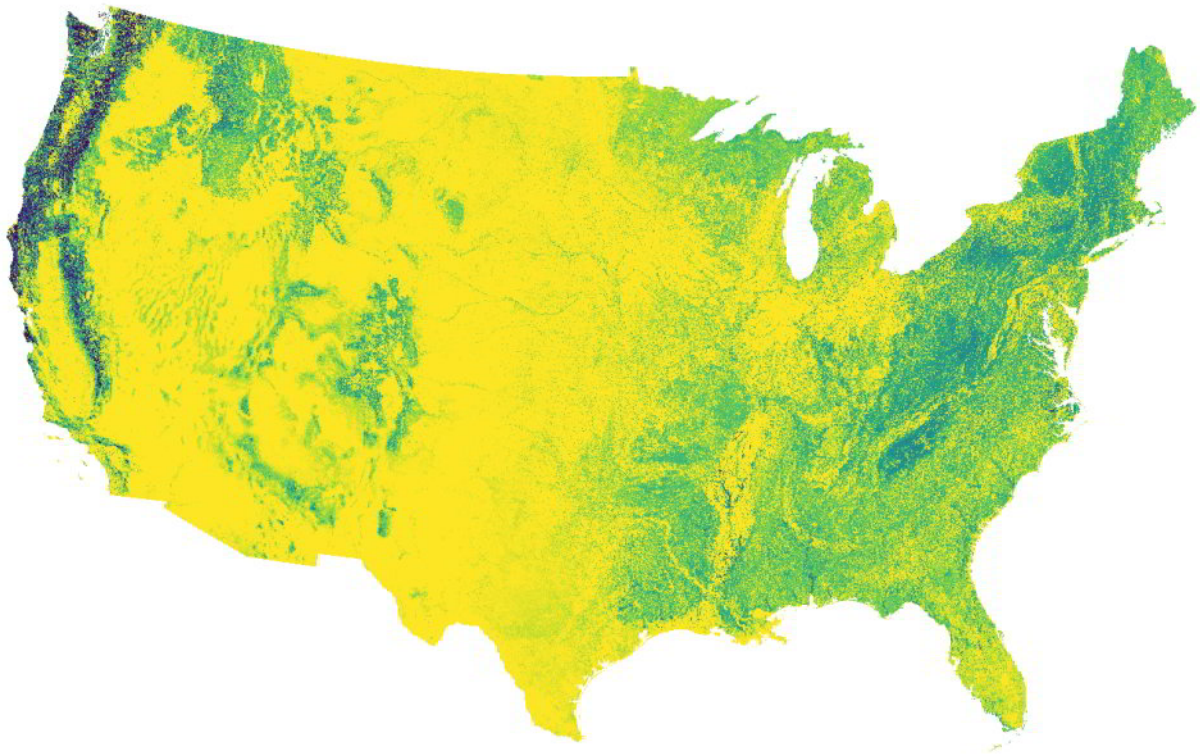
LT-COVER Biomass (NBCD FIA) v1

Annual 30-meter gridded biomass estimates for the conterminous United States 1984-2017



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Documentation v1
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Summary

The LT-COVER Biomass (NBCD FIA) data are 30-meter gridded annual biomass estimates for the conterminous United States (CONUS) for years 1984-2017. They are modeled after the above-ground, live, dry biomass estimates (NBCD_MZxx_FIA_ALD_biomass) provided by Kellndorfer et al. (2013). The data were generated by a spatiotemporal exploratory model (STEM) (Hooper and Kennedy, 2018, code) that relied on the Kellndorfer data for training and Landsat surface reflectance time series observations, along with topographic variables, as predictors. The resulting model (~80,000 models) was then applied to all years in the annual time series. To achieve prediction stability through time using a single model, the Landsat data was first fitted to spectral-temporal trends using the LandTrendr (Kennedy et al., 2018b, 2010, code) segmentation algorithm. An accuracy assessment based on agreement between the reference data and the predicted data for the year 2000 (year trained on) shows that the median of median absolute error among 67 assessment zones is four Mg/ha and the median correlation coefficient is 0.87.

Data Access

Please visit https://github.com/eMapR/LT-COVER for information regarding data access options.

Metadata

The following table (Table 1) describes the original characteristics of the dataset. Note that data may be delivered with deviating charactersitics.

Characteristic	**Value**
Exent	Conterminous United States (CONUS)
Projection	EPSG:5070
Projected unit	meter
Projected bounds	ulxy: (-2356060, 3172580), lrxy: (2258200, 272055)
Spatial resolution	30 m (x), 30 m (y)
Temporal resolution	Annual
Temporal duration	34 years (1984-2017)
Grid size	153809 columns, 96684 rows
Nodata value	-9999
Data type	Int16
Data unit	Megagrams per hectare (Mg/ha) above-ground, live, dry biomass

Table 1: Metadata.

Methods

Overview

The goal was to use 30 m spectral and topographic data to generate a model that would mimic the map of biomass created by Kellndorfer et al for the year 2000 and then apply the model to all year from 1984-2017. Variable selection was performed to reduce a total of 412 candidate predictors down to 10. A spatiotemporal exploratory model was generated from a stratified random sample of corresponding pixels in the Kellndorfer et al 2000 biomass training map and the 10 predictor variables. The model was applied to all years from 1984 to 2017 and aggregated using the median of intersecting model estimates. An accuracy assessment based on agreement between the reference data and the predicted data for the year 2000 was conducted on 67 assessment zones to reveil regional fidelity.

Prediction

Predictor Variables Selection

Combinations of Landsat surface reflectance image data, derived spectral change information, and topographic variables constituted a total candidate pool of 412 variables (Table 2). Through a process of variable selection, the top ten variables were selected as the final predictor set (Table 3). The initial candidate pool included eight spectral indices, with all combinations of them defining spectral-temporal segmentation in the LandTrendr algorithm and being fitted to segmentation. For each of the spectral variables, the spectral delta from the previous year to the current year was included, as well as the number of years since the last spectral-temporal segment vertex for each segmentation-defining spectral index. These variables were generated for three seasons, spring (April 15-July 15), summer (June 15-September 15), and autumn (August 15-November 15). Additionally, elevation, aspect, topographic position index, and slope were included. The ten best variables from the total pool were selected by sequential forward floating search to find a near-optimal subset of candidate predictors. Variable performance was based on successfully characterizing land attributes (NLCD land cover, canopy cover, and impervious surface cover) from a sample of pixels drawn from 20 regions representing a spatial subset for each of the classes in the EPA level II ecoregion dataset (Omernik and Griffith, 2014).

Predictor	**Description**	**Citation**
Red[1][4]	Red band (0.63-0.69 μm)	
SWIR1[1][4]	Shortwave infrared band (1.55-1.75 μm)	
NBR[1][4]	Normalized Difference Burn Ratio	(Key and Benson, 2005)
NDSI[1][4]	Normalized Difference Snow Index	(Hall et al., 1995)
NDVI[1][4]	Normalized Difference Vegetation Index	(Rouse Jr et al., 1974)
TCB[1][4]	Tasseled Cap Brightness	(Crist, 1985)
TCG[1][4]	Tasseled Cap Greenness	(Crist, 1985)
TCW[1][4]	Tasseled Cap Wetness	(Crist, 1985)
Delta[2][4]	spectral difference from previous year	
Tsince[3][4]	Time since last vertex (years)	
Elevation	Elevation above sea level	
Slope	Topographic slope	
Aspect	Topographic aspect	
TPI	Topographic postional index	(Weiss, 2001)

Table 2: Candidate predictor variables.
[1] Used as a LandTrendr segmentation index and was also fitted to segmentation by all other indices.
[2] Calculated for all combinations of all [1] predictors
[3] Calculated only once for each [1] index segmented with by LandTrendr
[4] Represented by three Landsat compossite seasons: spring (April 15-July 15), summer (June 15-September 15), and autumn (August 15-November 15).

Predictor	Description
ndsi_summer_b3	Landsat red band time series fitted to LandTrendr segmentation of summer NDSI composite
ndsi_summer_tcg	Landsat TCG time series fitted to LandTrendr segmentation of summer NDSI composite
ndsi_autumn_tcb	Landsat TCB time series fitted to LandTrendr segmentation of autumn NDSI composite
ndvi_spring_b5	Landsat SWIR1 time series fitted to LandTrendr segmentation of spring NDVI composite
ndvi_spring_deltab5	Landsat SWIR1 Delta derived from SWIR1 fitted to LandTrendr segmentation of spring NDVI composite
ndvi_spring_ndsi	Landsat NDSI time series fitted to LandTrendr segmentation of spring NDVI composite
tcb_autumn_ndsi	Landsat NDSI time series fitted to LandTrendr segmentation of autumn TCB composite
tcb_autumn_ndvi	Landsat NDVI time series fitted to LandTrendr segmentation of autumn TCB composite
elevation	Topographic elevation
slope	Topographic slope

Table 3: Final set of predictor variables.

Predictor Data Generation

Spectral variable generation was done on the Google Earth Engine (Gorelick et al., 2017) platform. For each of the three seasons, a collection of USGS surface reflectance images (Masek et al., 2006; Vermote et al., 2016) from 1984 to 2017 was assembled. The collections included images from Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) sensors. Each image of the collections were masked to exclude clouds, cloud shadows, and snow using the CFMASK mask (Zhu et al., 2015), which is provided with the surface reflectance product. Additionally, OLI image bands 2, 3, 4, 5, 6 and 7 were transformed to the spectral properties of ETM+ bands 1, 2, 3, 4, 5 and 7, respectively, using slopes and intercepts from reduced major axis regressions reported in Table 2 of Roy et al. (2016). Images from within each seasonal collection were composited using a medoid approach: for a given image pixel, the medoid is the value for a given band that is numerically closest to the median of all corresponding pixels among the images considered.

Medoid compositing was performed for each year per season collection and included images from any sensor contributing to the annual set of observations for the year being processed. The result was a single multi-band image, per year, free of clouds and cloud shadows, representing median spring, summer, and autumn season surface reflectance. From these annual medoid composites, indices from Table 3 were calculated and provided as segmentation and fit-to-vertice inputs to the LandTrendr spectral-temporal segmentation algorithm (Kennedy et al., 2010, 2018b). LandTrendr identifies breakpoints (referred to as vertices) in an image pixel time series between periods of relatively consistent spectral trajectory. From these breakpoints, a new time series is constructed, where each annual observation is interpolated to fit on a line segment between vertices (Figure 3). The result is an idealized, trajectory-based, time series free from noise, where each observation is placed in the context of a spectral-temporal trend. The LandTrendr parameters used can be found in Table 4

Parameter	Value
maxSegments	6
spikeThreshold	0.9
vertexCountOvershoot	3
preventOneYearRecovery	true
recoveryThreshold	0.25
pvalThreshold	0.05
bestModelProportion	0.75
minObservationsNeeded	6

Table 4: LandTrendr parameters used.

Modeling

A spatiotemporal exploratory model (STEM) was used to construct relationships between the biomass estimates of kellndorfer et al and the predictor variables described previously. A STEM is an ensemble of locally defined, randomly located, spatially overlapping decision trees culminating in a final prediction by aggregating over all overlapping pixels with a specified statistical function, such as the median (Figure 1). Both the potential spatial coordinates of the training sample and the prediction domain for each decision tree are spatially limited by a support set. The method produces a seamless broad-extent map that reflects variability at the spatial scale of each constituent support set without the need for pre-define modeling regions. The final value of each pixel was determined from a population of approximately 100 estimates representatives (in this particular dataset) from randomly overlapping support sets.

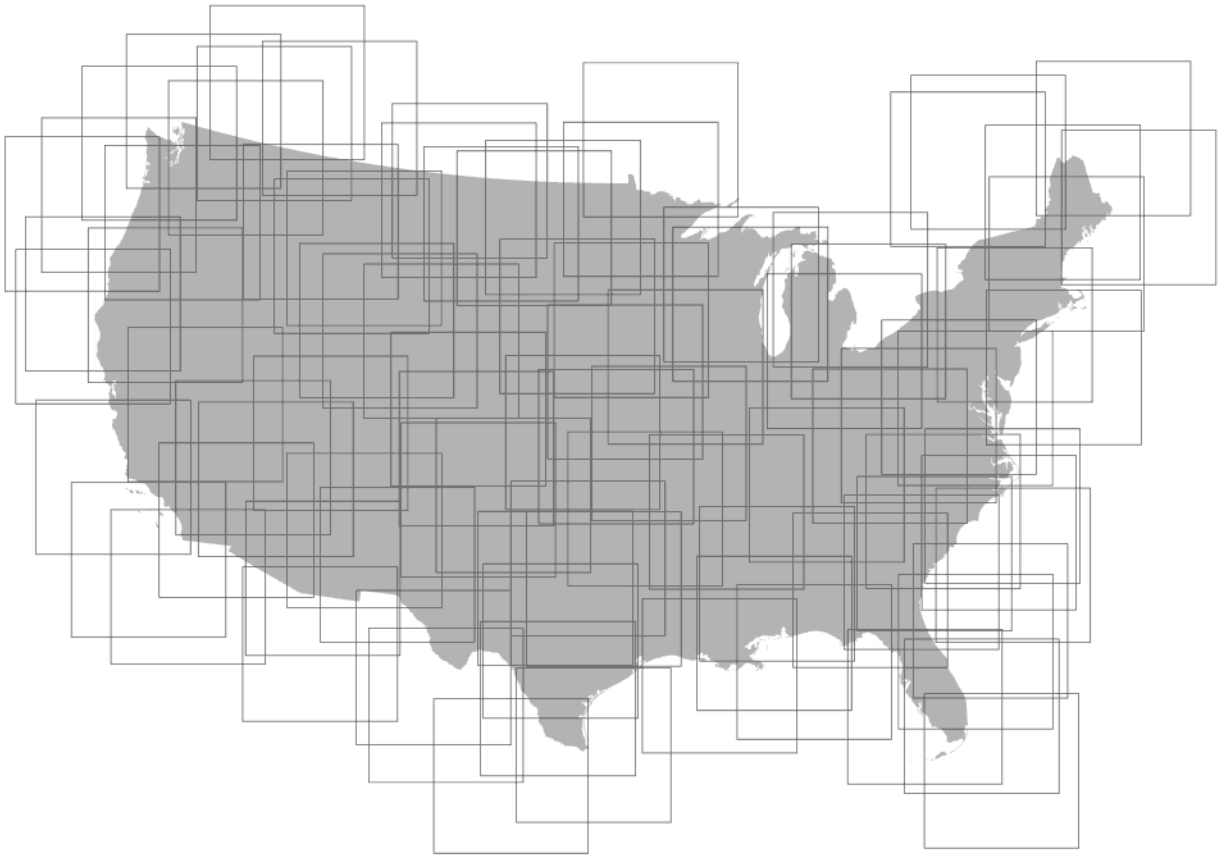


Figure 1: Conceptual representation of STEM: an ensemble of locally defined, randomly located, spatially overalpping decision trees culminating in a final prediction by aggregating over all overlapping pixels with a specified statistical function.

A stratified random sample of pixels from the kellndorfer et al 2000 map were selected according to parameters listed in Table 5. Predictor variable values were then extracted from year 2000 for each pixel identifed in the sample. The model was then trained using parameters presented in Table 6

Parameter	**Value**
bins	-1:1, 1:50, 50:100, 100:150, 150:200, 200:300, 300:400, 400:600, 600:800
pct_train	1
data_type	continuous
n_tiles	15, 25
sampling_scheme	proportional
min_sample	0.03
max_sample	0.3
n_per_tile	30000

Table 5: Seleted STEM *get_stratified_random_pixels.py* parameters.

Parameter	Value
cell_size	30000, 30000
support_size	150000, 150000
sets_per_cell	4
min_obs	500
model_type	regressor

Table 6: Seleted STEM *train_stem.py* parameters.

Parameter	Value
support_size	150000, 150000
n_tiles	60, 90

Table 7: Seleted STEM *predict_stem.py* parameters.

Model Application

The resulting STEM model trained from the year 2000 was applied to all years from 1984-2017. A single model applied throught time is reasonable because all of the time series data was fitted to trends using the LandTrendr spectral-temporal segmenation algorimth, which places each value in a pixel's time series along lines defined by breakpoints where durable change is statistcally recognized. This acheives a high level of prediction consistency and expectation i.e. biomass estimates are not bouncing around year-to-year because of inherent variablity in the raw surface reflectance data. Examples of other projects that have used LandTrendr fitted spectral data to apply a single model through time include: (Hooper and Kennedy, 2018; Vogeler et al., 2018; Kennedy et al., 2018a). The following series of figures (Figure 2, Figure 3, Figure 4, Figure 5) describe the LandTrendr segmentation and time series fitting processes.

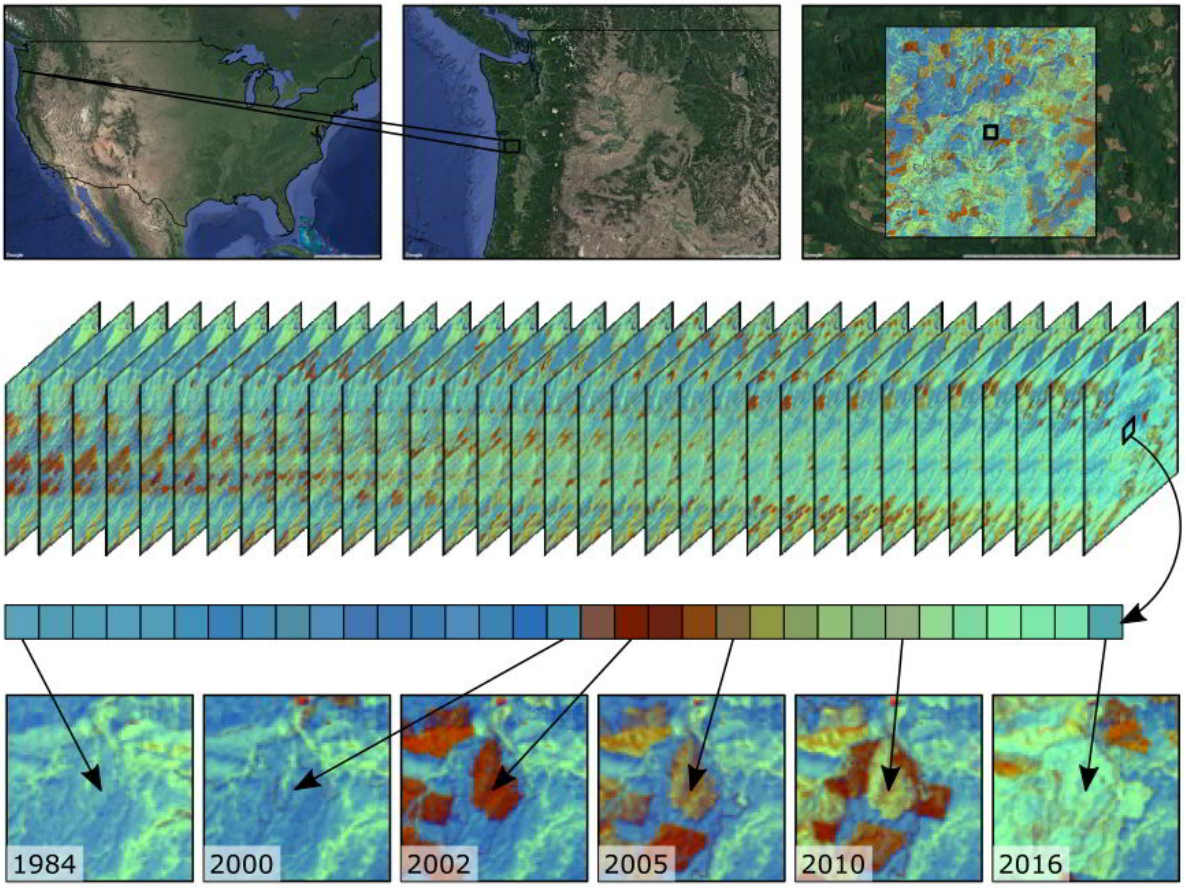


Figure 2: Every pixel tells a story. Landsat provides a historical record of the character of landscapes. By extracting a single pixel from a time series of Landsat imagery, it is possible to recount the state and change of the features composing the 1-hectare area of a pixel through time. In this example, we analyze the history of a conifer forest pixel from an industrial forest region of the Pacific Northwest (USA) that experiences a period of relative stability, a dramatic, rapid loss of vegetation, and subsequent regeneration.

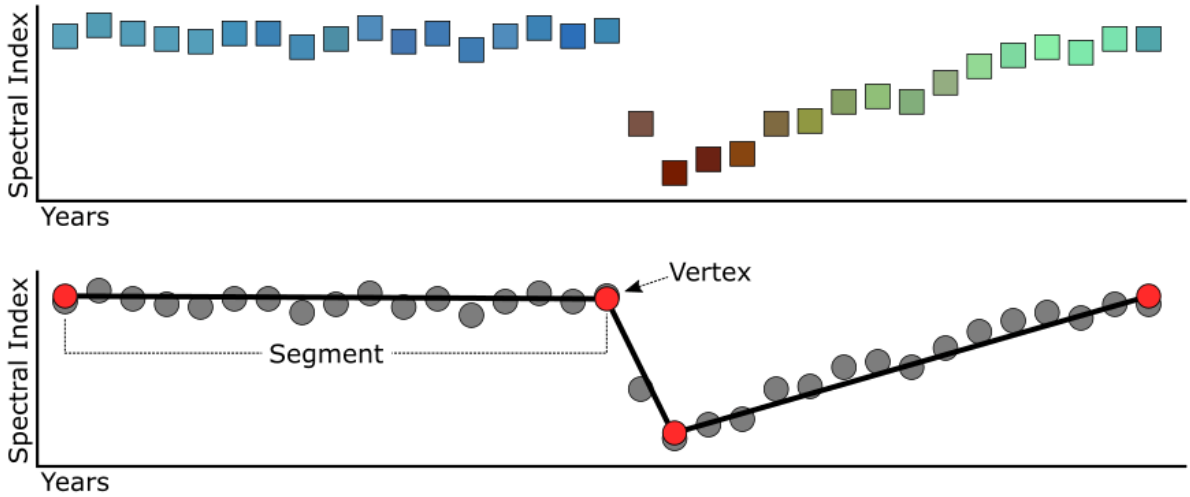


Figure 3: LandTrendr pixel time series segmentation. Image data is reduced to a single band or spectral index and then divided into a series of straight line segments by breakpoint (vertex) identification.

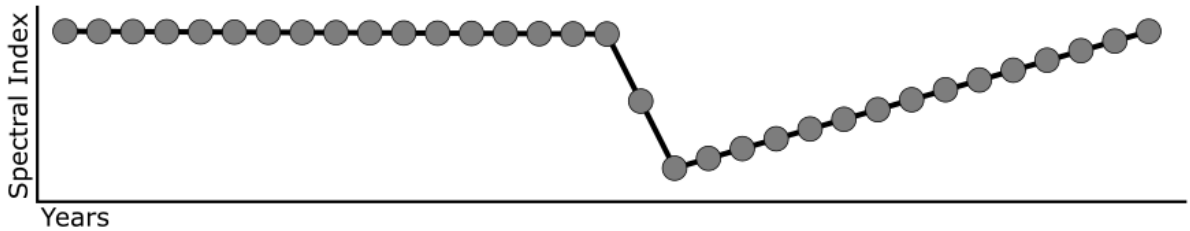


Figure 4: Hindsight-enhanced image time series data (fit-to-vertices). Identification of time series breakpoints or vertices allows the observations between vertices to be interpolated, removing extraneous information and placing each observation in the context of the trajectory it is part of. This is useful in filling missing observations because of cloud and shadow, and makes for more consistent annual map prediction.

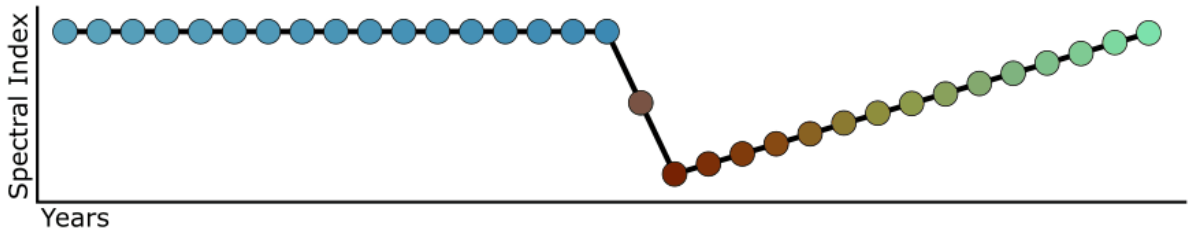


Figure 5: A stack of spectral representations can be standardized to the segmentation structure of a single spectral band or index. Here we are demonstrating the standardization of tasseled cap brightness, greenness, and wetness to the segmentation structure of NBR. This allows us to take advantage of multi-dimensional spectral space to describe the properties of spectral epochs and breakpoints to predict land cover, change process, and transitions from a consistent perspective (NBR).

Accuracy Assessment

An accuracy assessment comparing the pixel level agreement between the reference map and the prediction map for the corresponding year of 2000 was conducted. The assessment was broken into 67 zones Figure 6 as initially defined by Homer and Gallant (2001) for use in developing the NLCD 2001 Land Cover map (Homer et al., 2004), and modified slightly for use by Kellndorfer and the LANDFIRE program for defining modeling regions. The modified Homer and Gallant (2001) zone map can be downloaded here https://github.com/eMapR/LT-COVER/blob/master/vector/conus_mapszones_landfire.zip and the version used in our accessment, which was clipped to the boundary of the LT-COVER data can be downloaded here https://github.com/eMapR/LT-COVER/blob/master/vector/conus_mapzones_lt-cover.zip.

Errors present in the training data could have been propagated to our maps

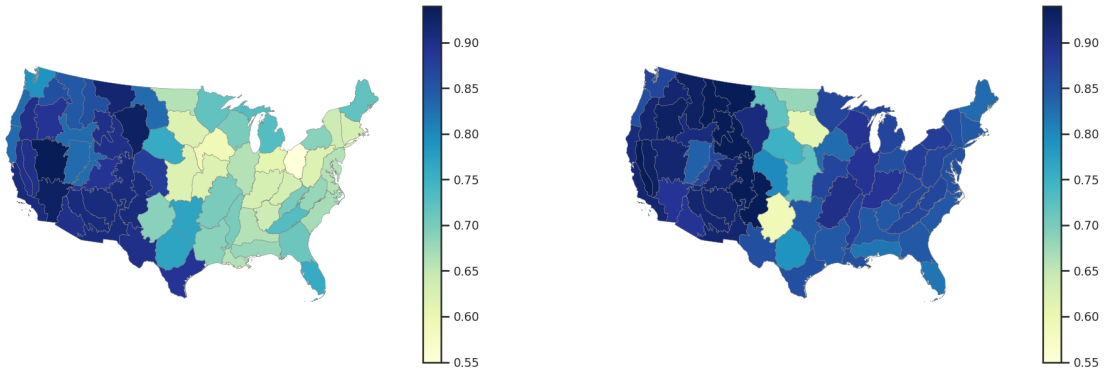
Figure 6: Accuracy assessment zone map

1	2	3	4	5	6	7	8	9	10	12
13	14	15	16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31	32	33	34
35	36	37	38	39	40	41	42	43	44	45
46	47	48	49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64	65	66	98
99										

Table 8: Zone map table. Click zones numbers to hyperlink to a specific zone's accuracy assessment.

	Zero Included	**Zero Excluded**
r	0.87	0.76
MAE	4	15
μAE	13.6	19.1

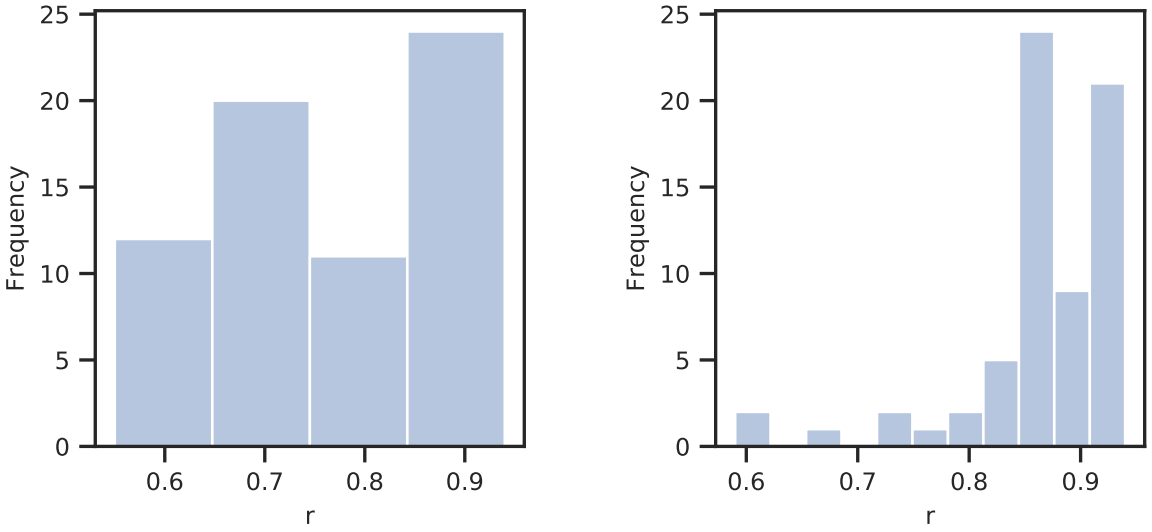
Table 9: Overall Accuracy of the map defined by the correlation coeffient (r), median absolute error (MAE), and mean absolute error (μAE) per map zone, reduced using median.



(a) Zero excluded

(b) Zero included

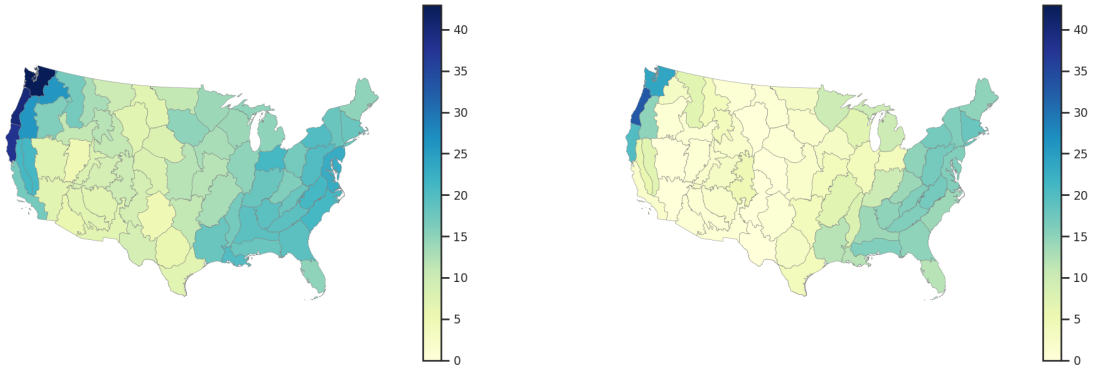
Figure 7: Pixel-level correlation coefficient (r) by zone - spatial distribution



(a) Zero excluded

(b) Zero included

Figure 8: Pixel-level correlation coefficient (r) by zone - histogram



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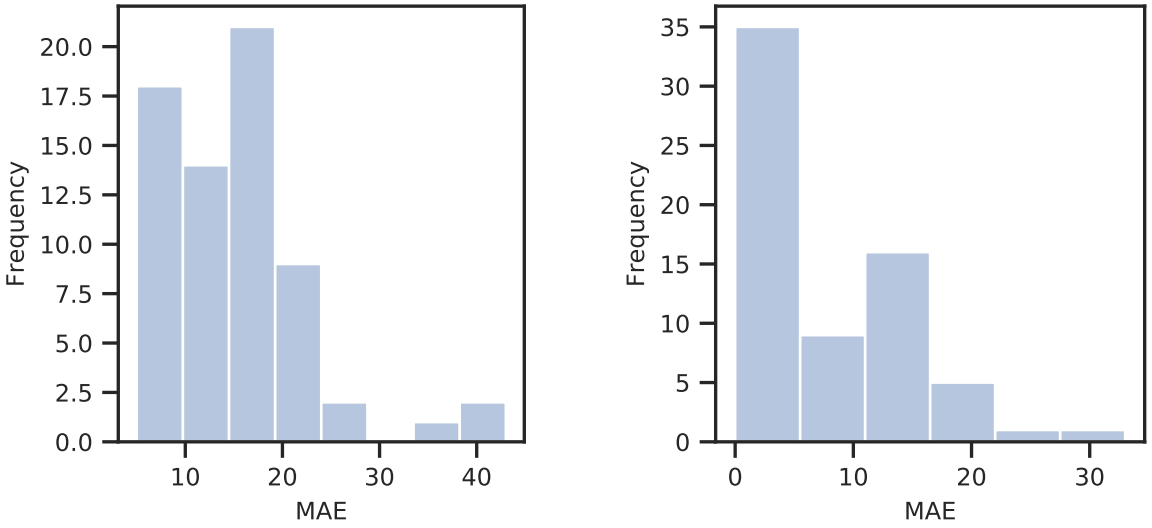
(b) Zero included

Figure 9: Pixel-level median absolute error (MAE) by zone - spatial distribution



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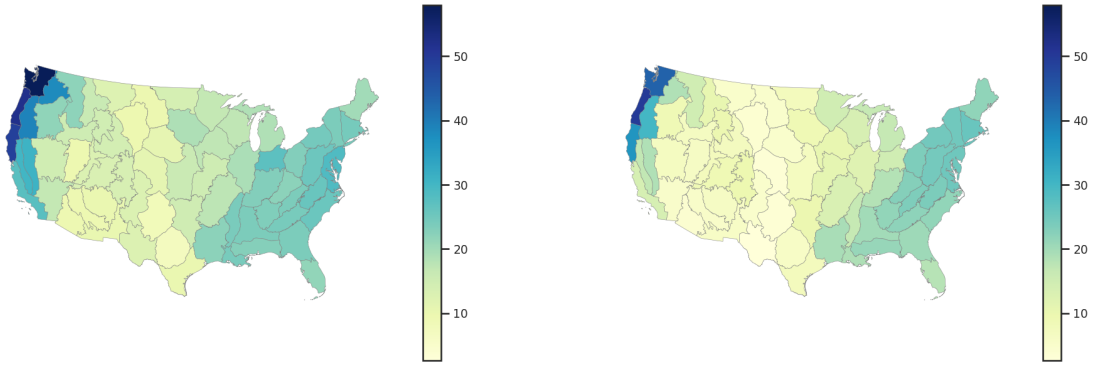
(b) Zero included

Figure 10: Pixel-level median absolute error (MAE) by zone - histogram



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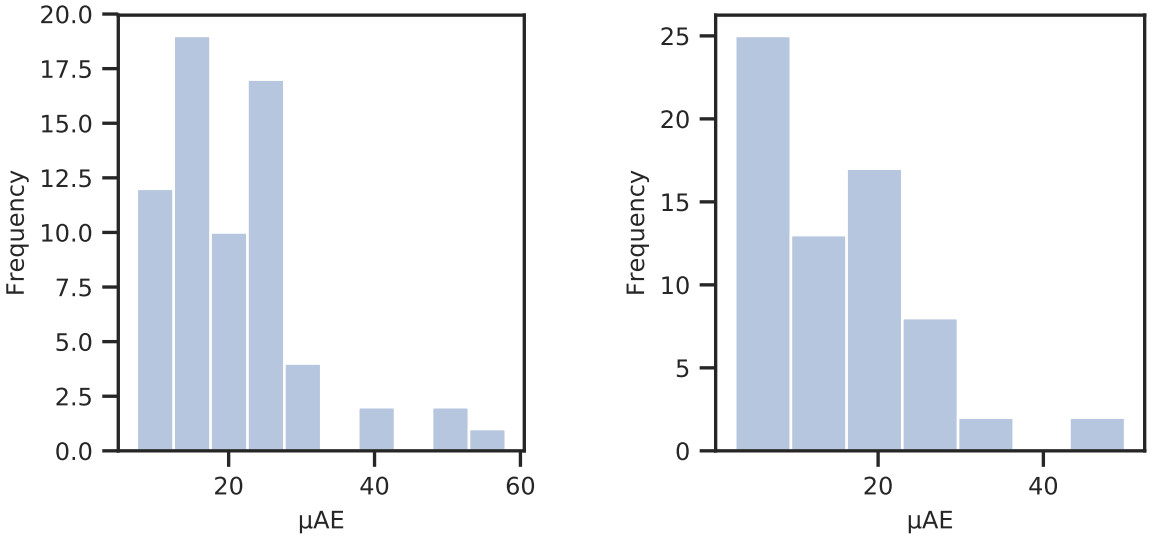
(b) Zero included

Figure 11: Pixel-level mean absolute error (µAE) by zone - spatial distribution



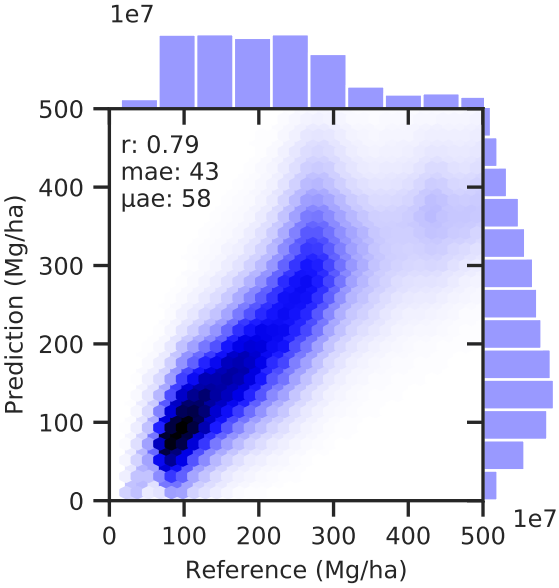
(a) Zero excluded

(b) Zero included

Figure 12: Pixel-level mean absolute error (µAE) by zone - histogram

Zone 1

Zone map (zone 1)



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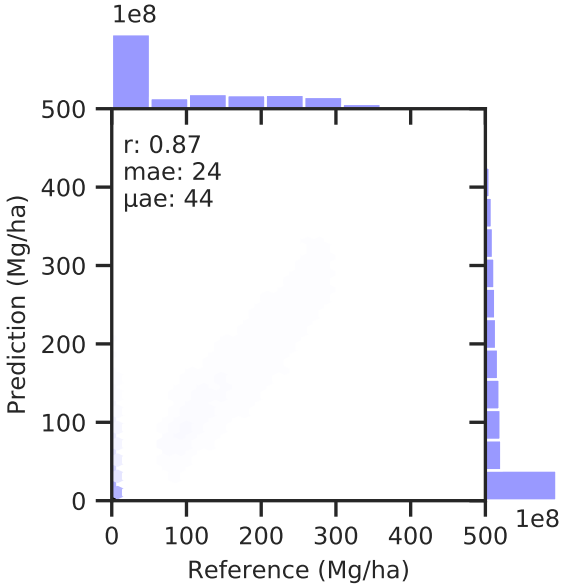
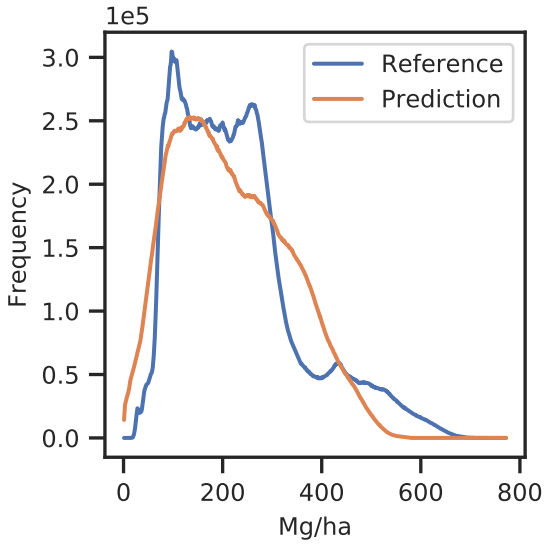


(b) Zero included

2-D frequency histogram (zone 1)



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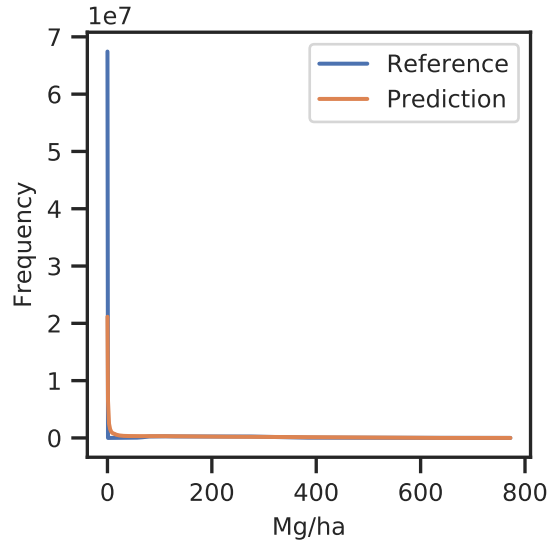

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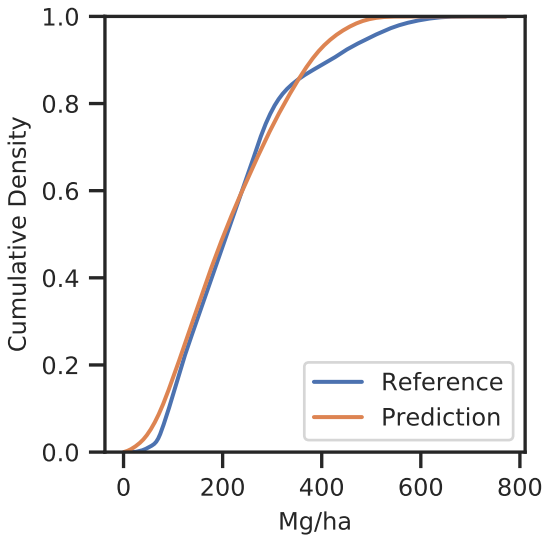
Ordinary frequency histogram (zone 1)



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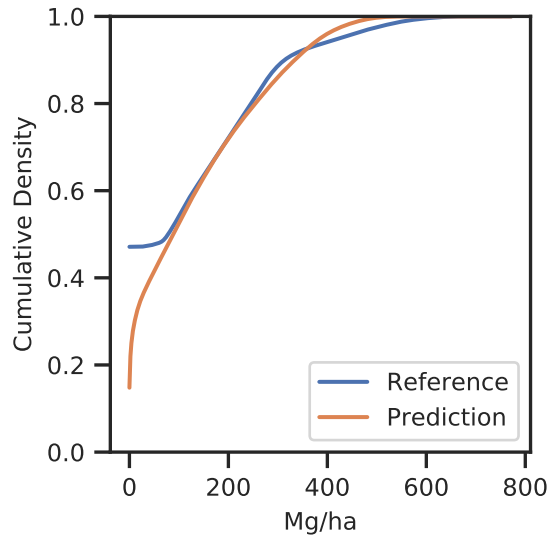


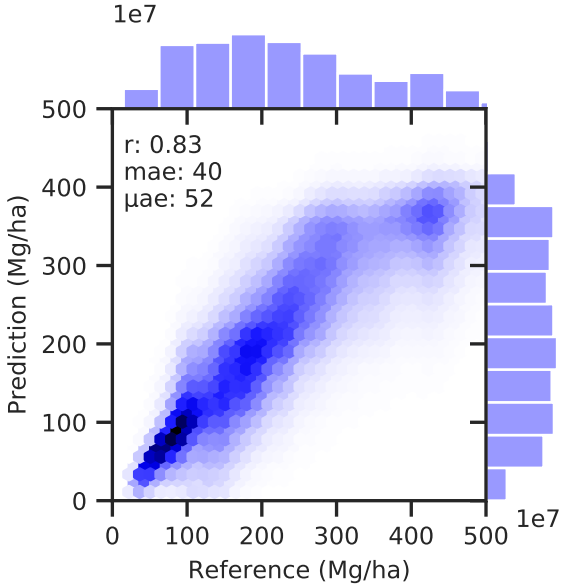
(b) Zero included

Cumulative density histogram (zone 1)

Return to zone table

Zone 2

Zone map (zone 2)



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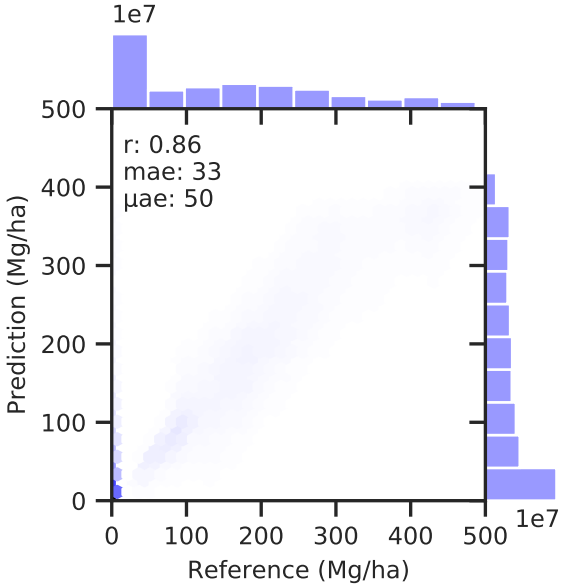

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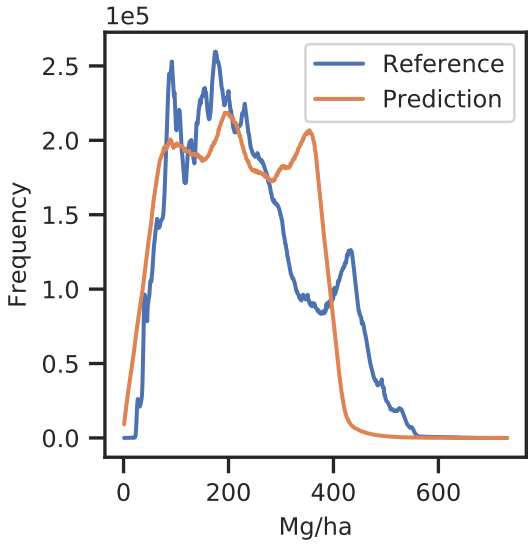
2-D frequency histogram (zone 2)



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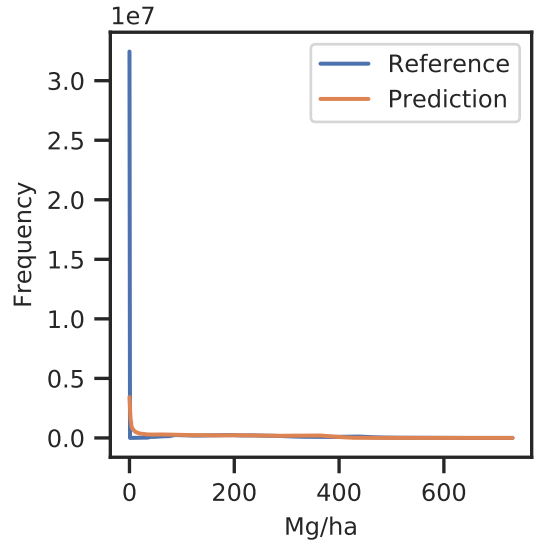

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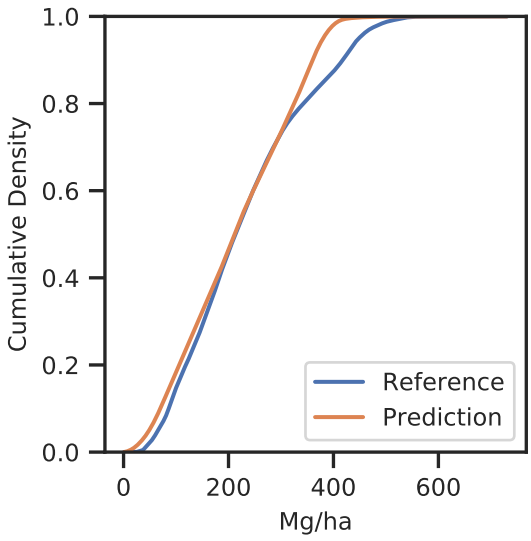
Ordinary frequency histogram (zone 2)



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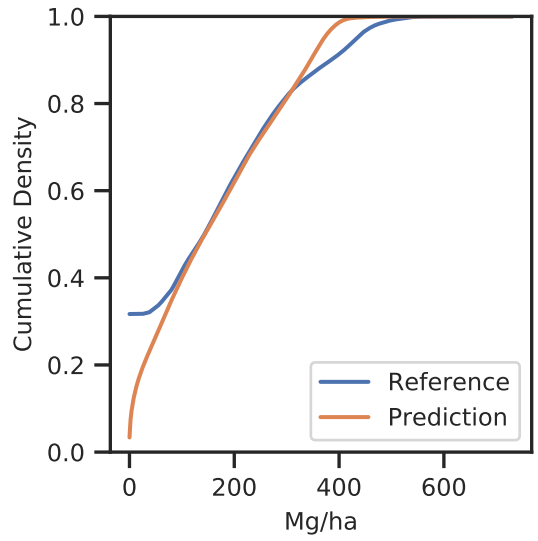


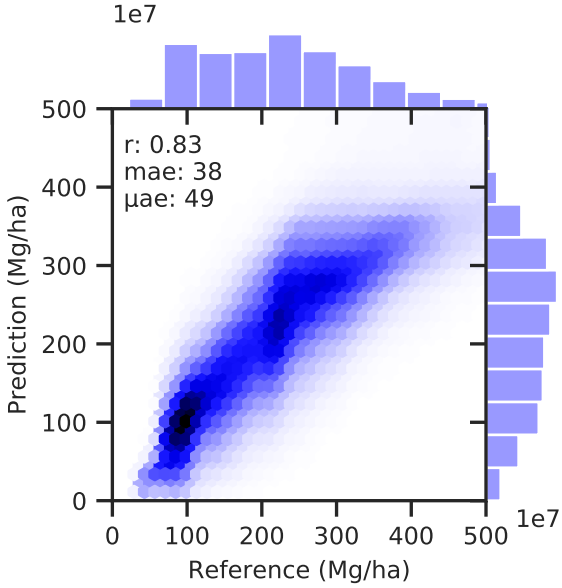
(b) Zero included

Cumulative density histogram (zone 2)

Return to zone table

Zone 3

Zone map (zone 3)



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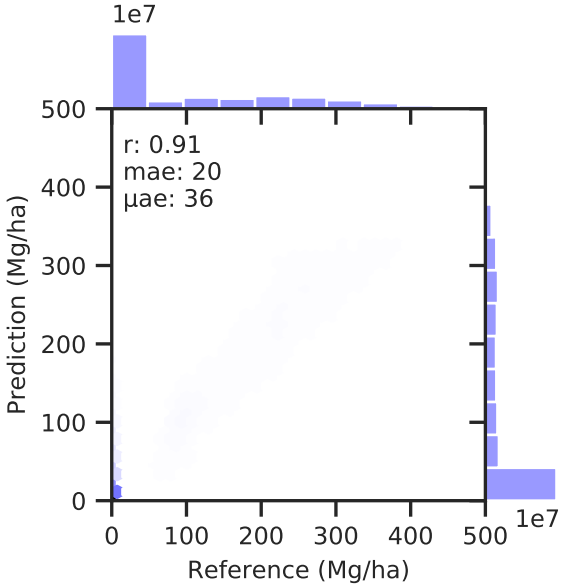

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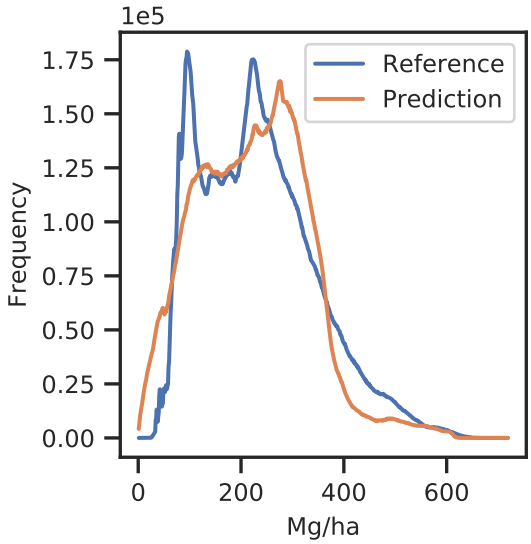
2-D frequency histogram (zone 3)



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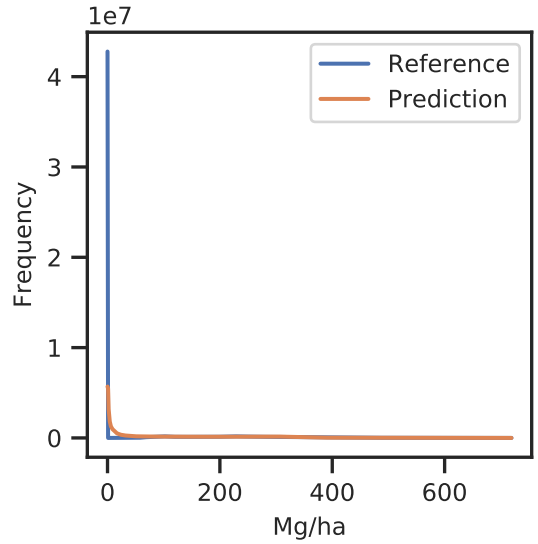
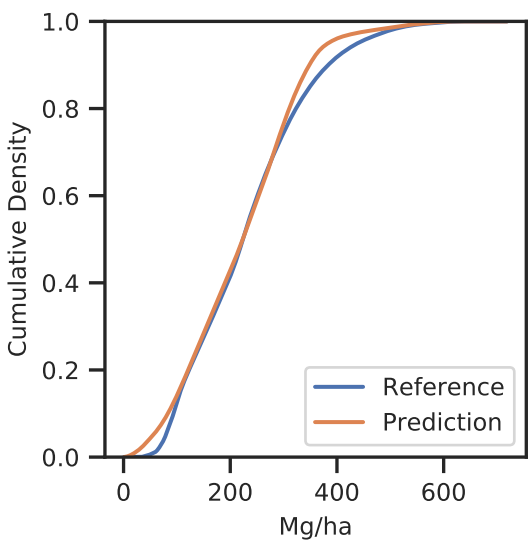
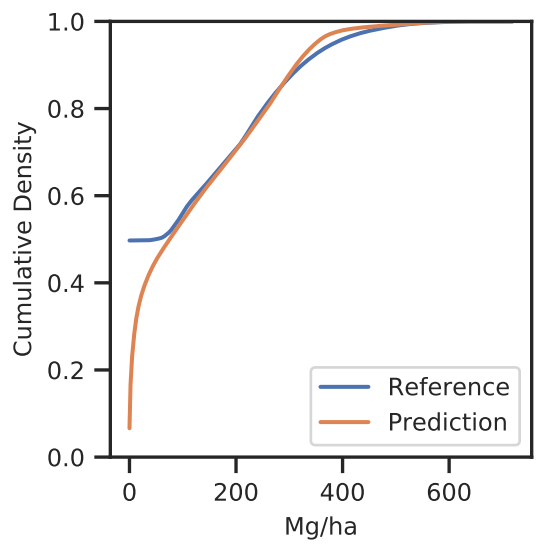


(b) Zero included

Ordinary frequency histogram (zone 3)



(a) Zero excluded



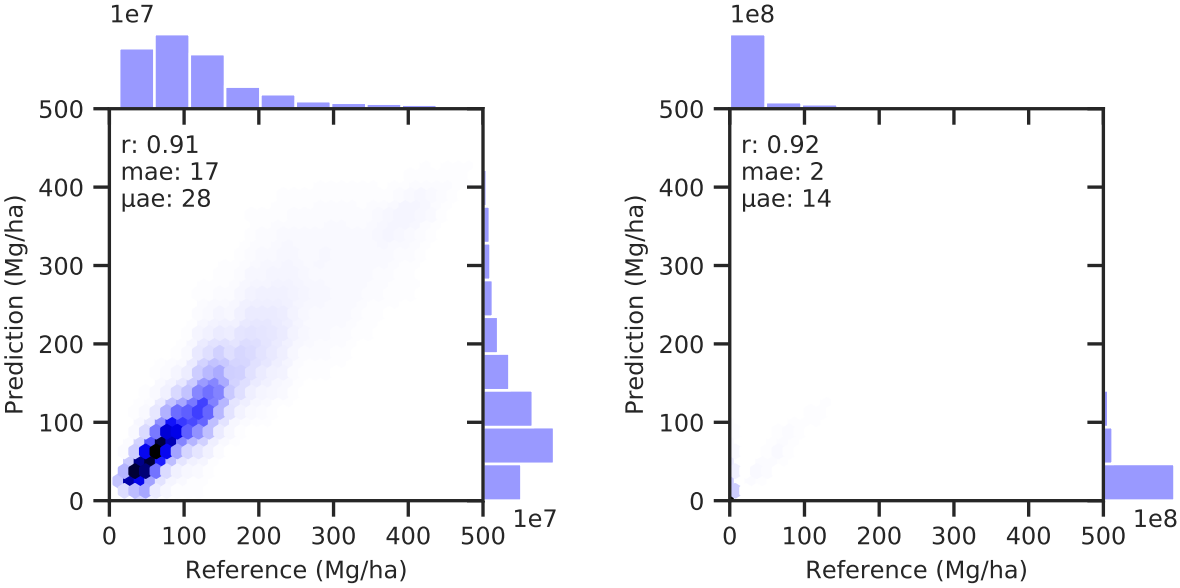
(b) Zero included

Cumulative density histogram (zone 3)

Return to zone table

Zone 4

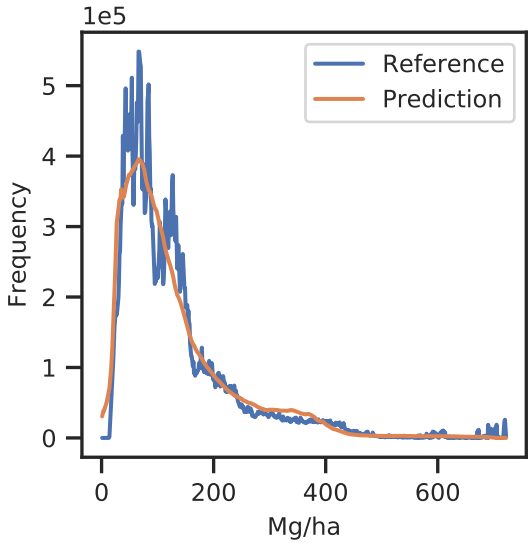
Zone map (zone 4)



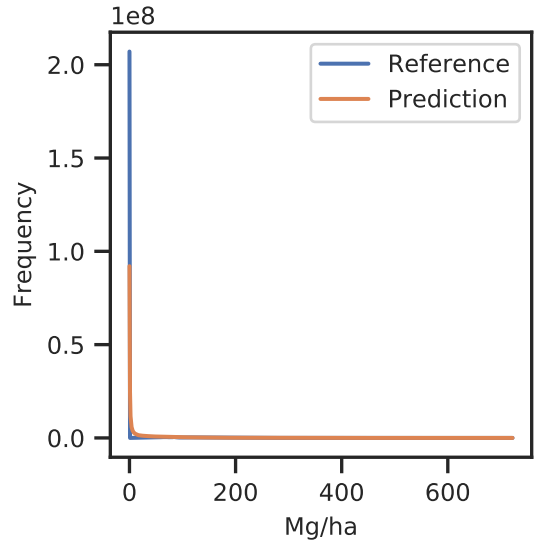
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 4)

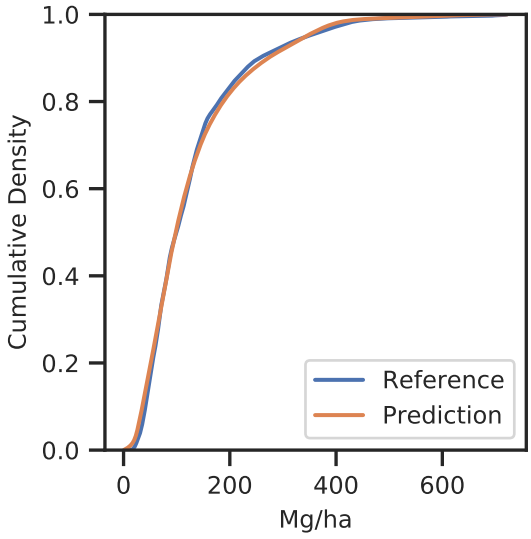


(a) Zero excluded

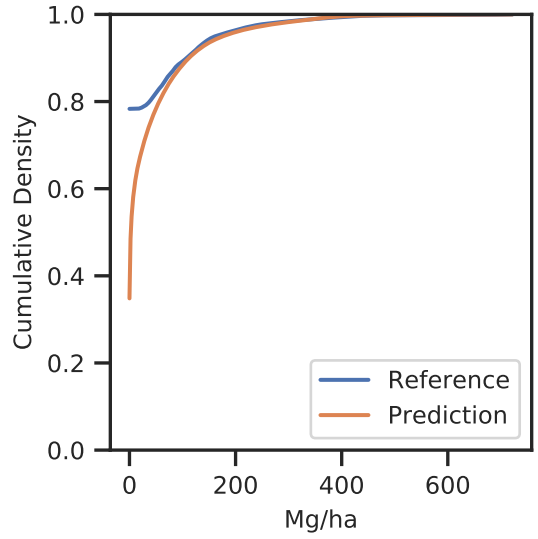


(b) Zero included

Ordinary frequency histogram (zone 4)



(a) Zero excluded



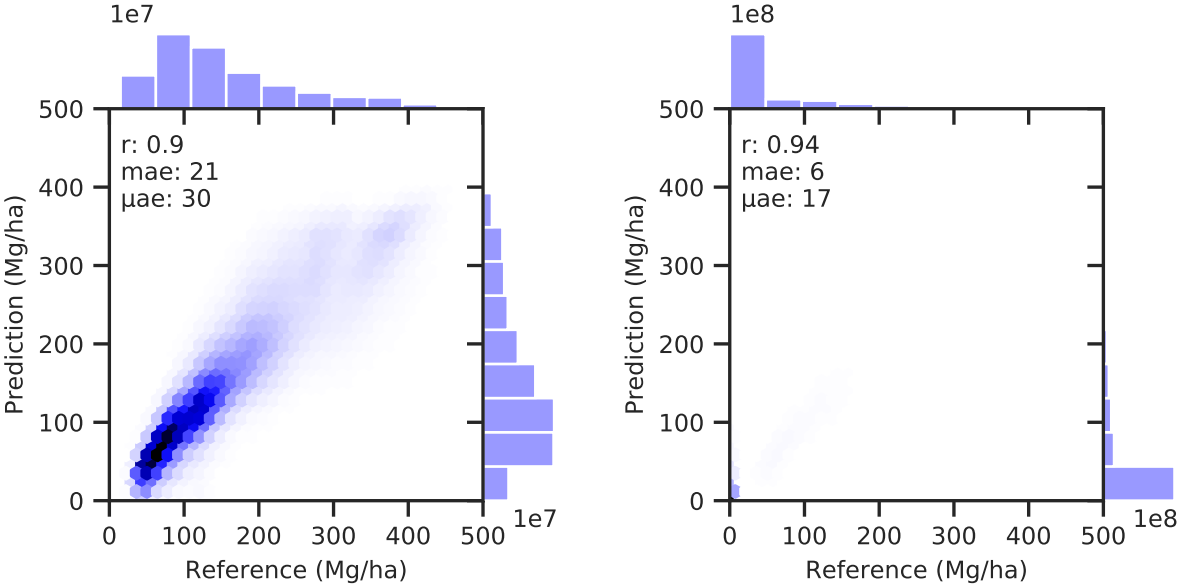
(b) Zero included

Cumulative density histogram (zone 4)

Return to zone table

Zone 5

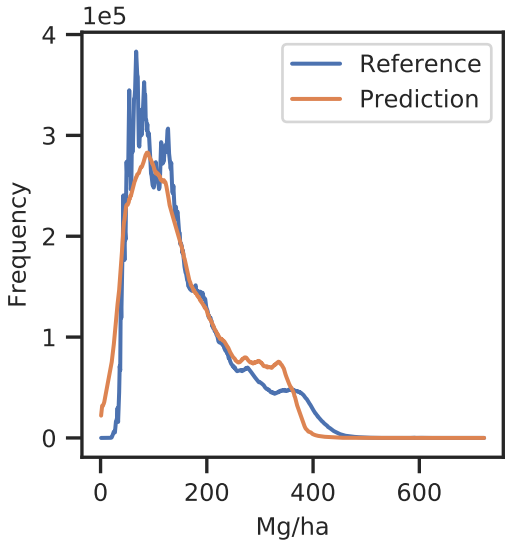
Zone map (zone 5)



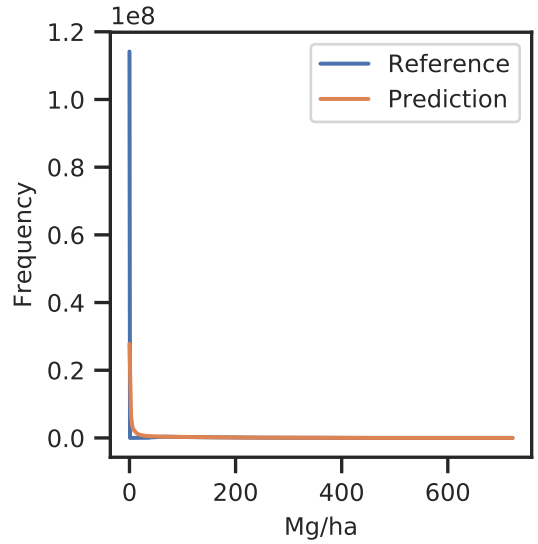
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 5)

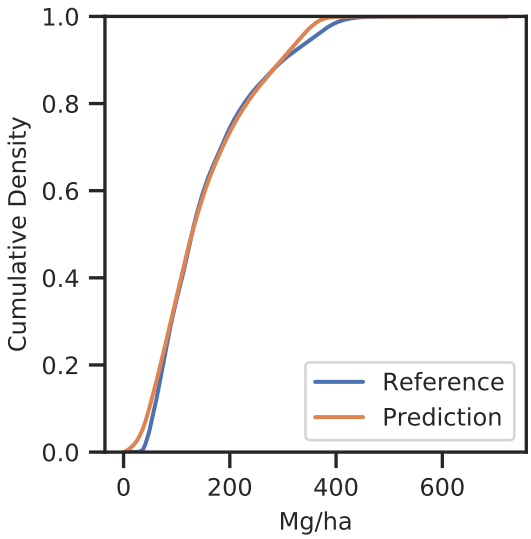


(a) Zero excluded

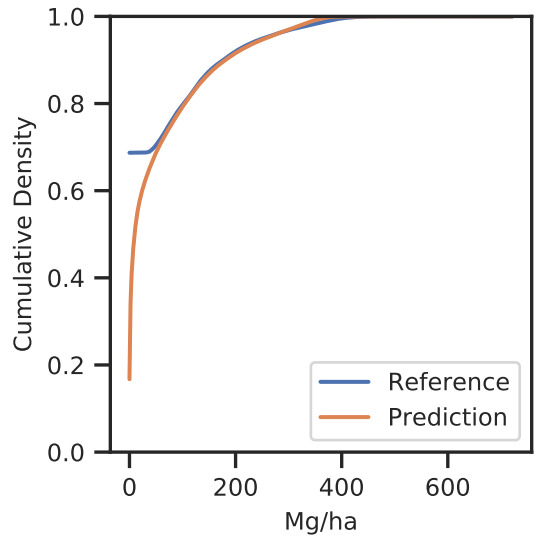


(b) Zero included

Ordinary frequency histogram (zone 5)



(a) Zero excluded



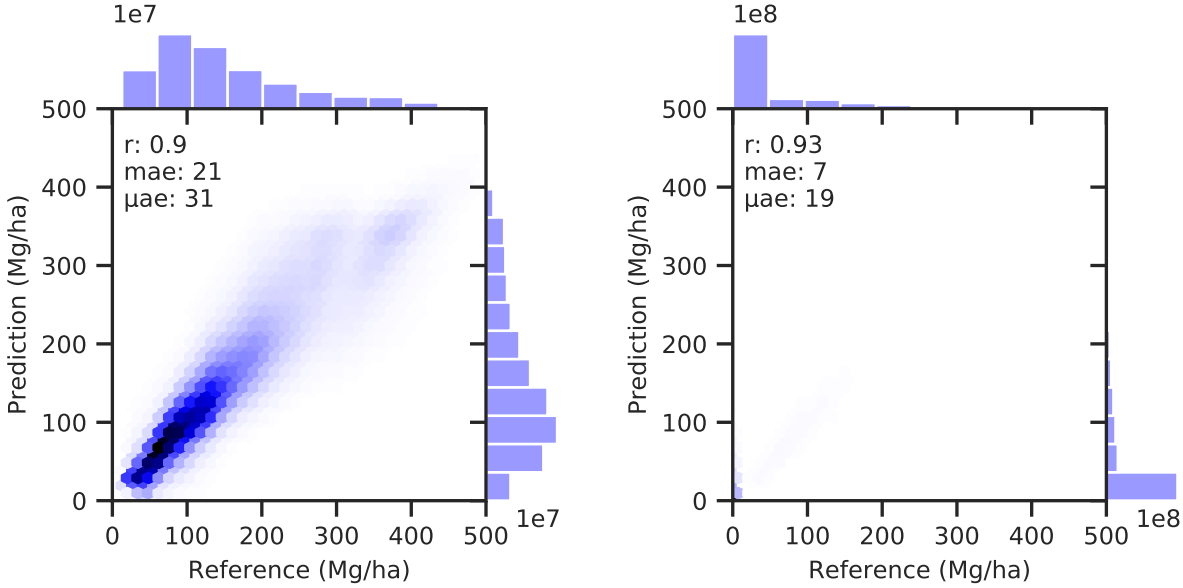
(b) Zero included

Cumulative density histogram (zone 5)

Return to zone table

Zone 6

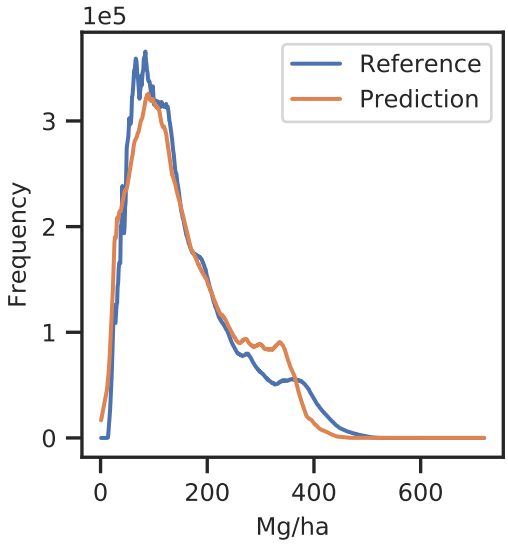
Zone map (zone 6)



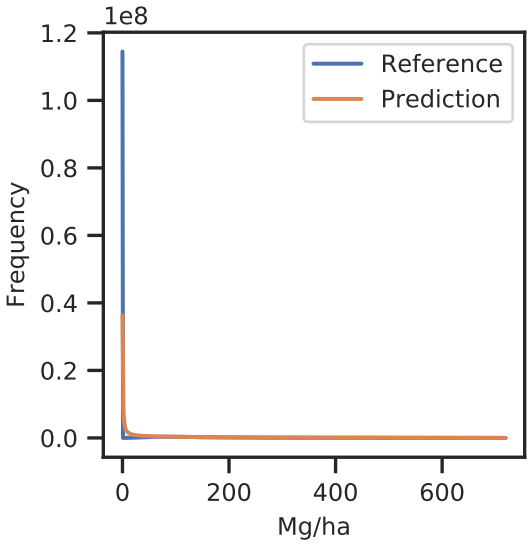
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 6)

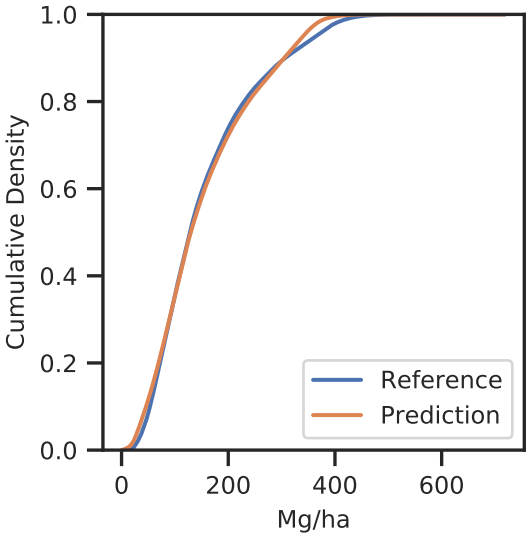


(a) Zero excluded

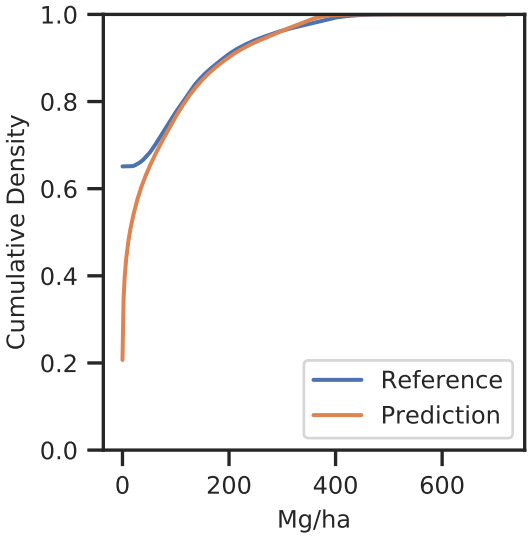


(b) Zero included

Ordinary frequency histogram (zone 6)



(a) Zero excluded



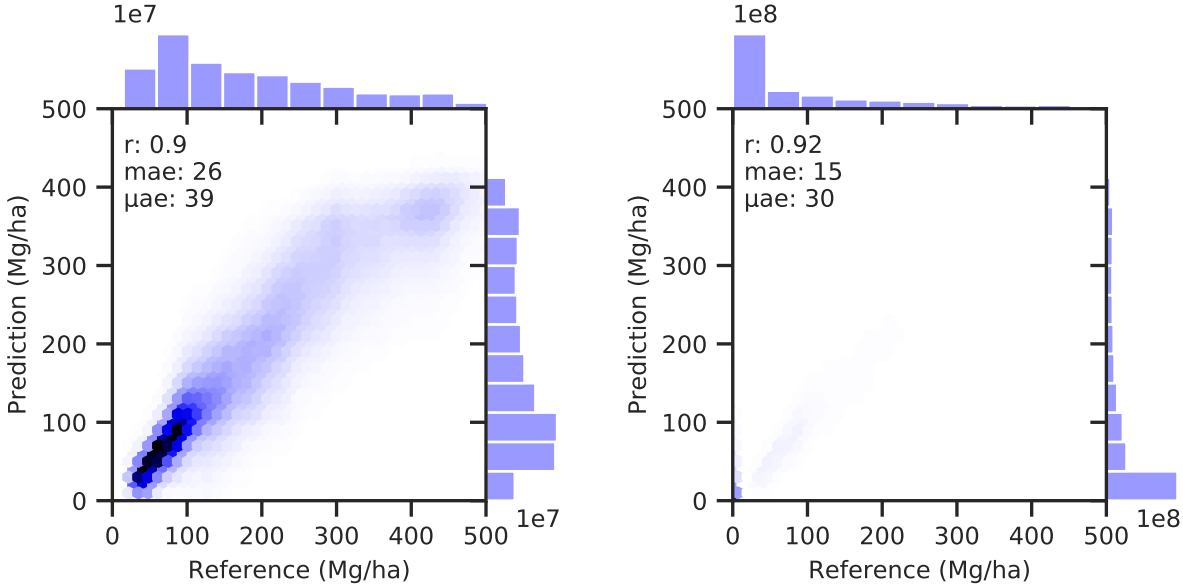
(b) Zero included

Cumulative density histogram (zone 6)

Return to zone table

Zone 7

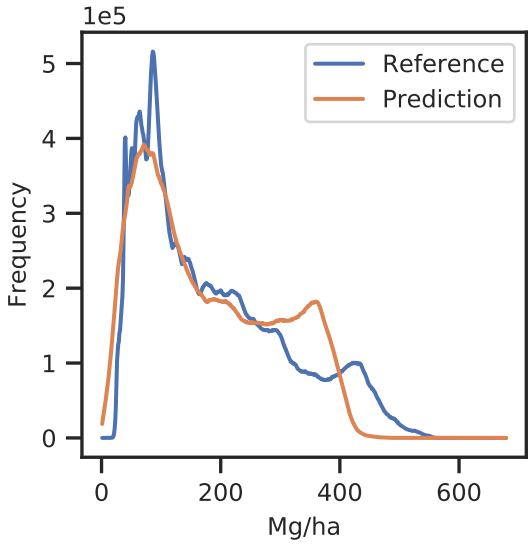
Zone map (zone 7)



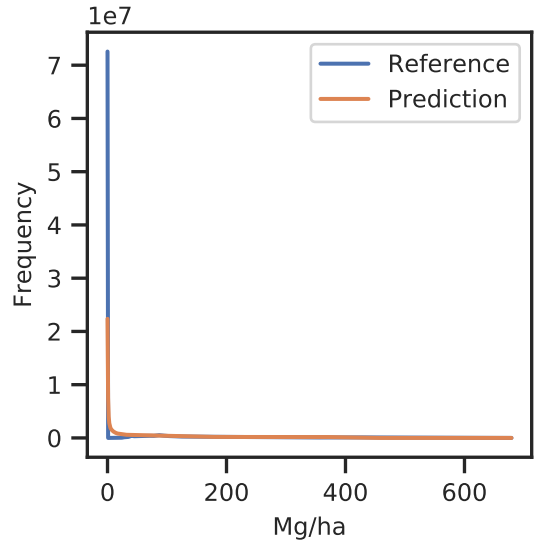
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 7)

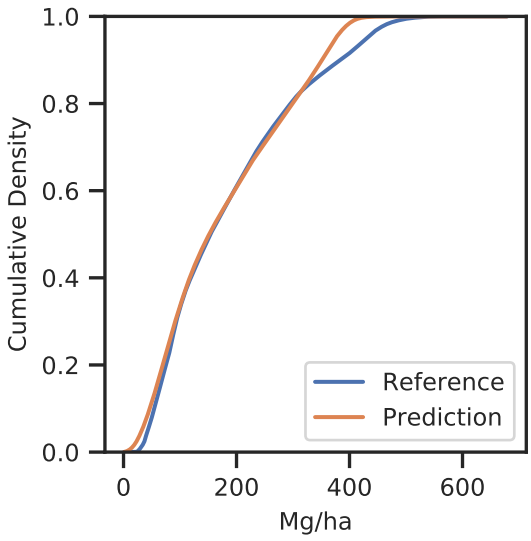


(a) Zero excluded

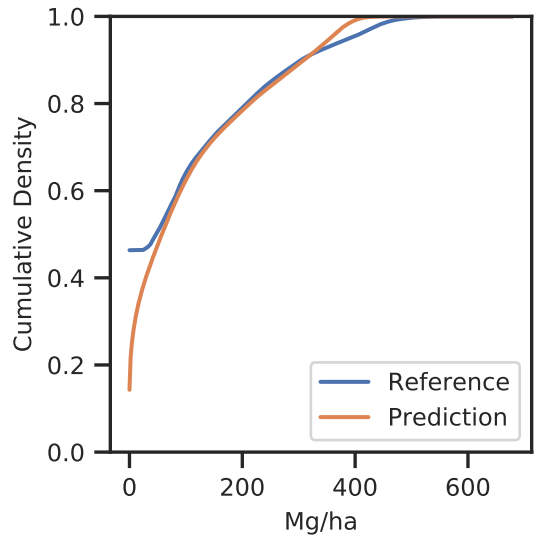


(b) Zero included

Ordinary frequency histogram (zone 7)



(a) Zero excluded



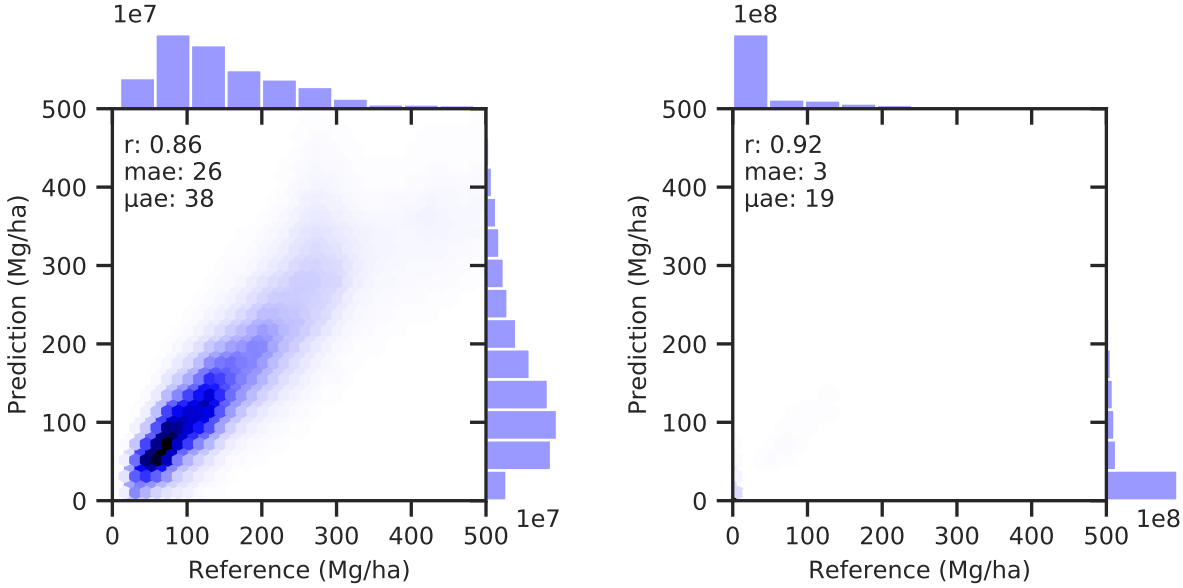
(b) Zero included

Cumulative density histogram (zone 7)

Return to zone table

Zone 8

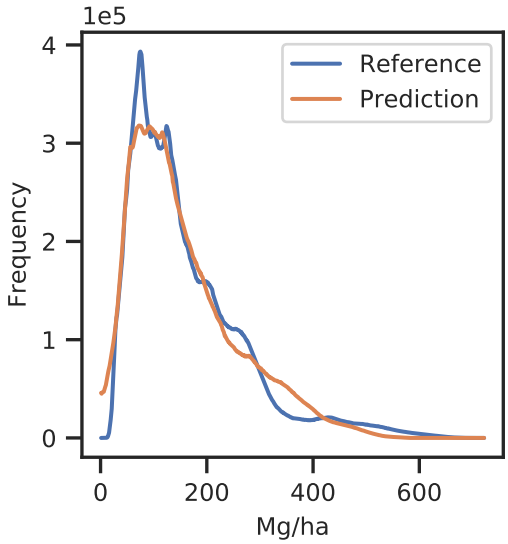
Zone map (zone 8)



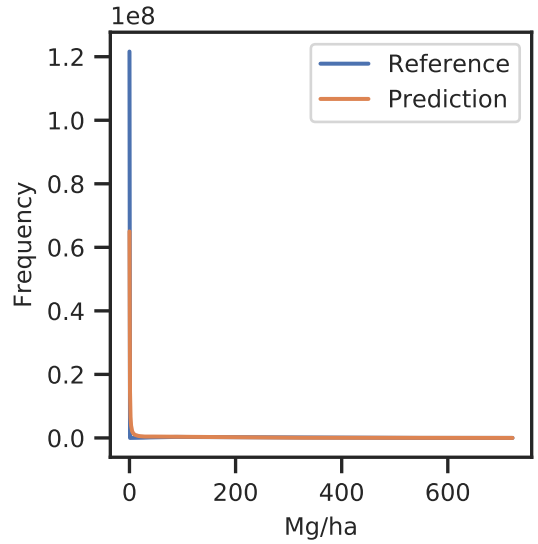
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 8)

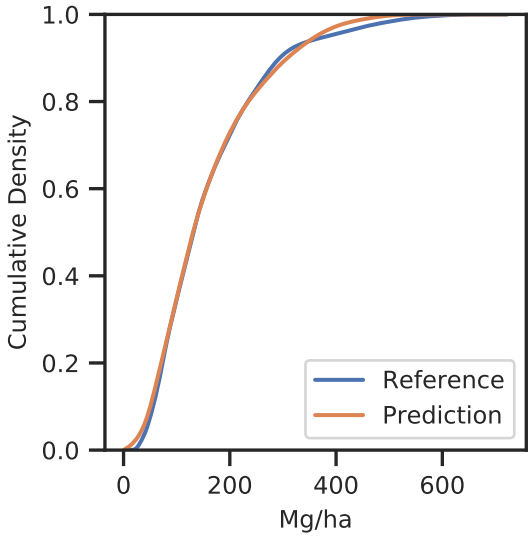


(a) Zero excluded

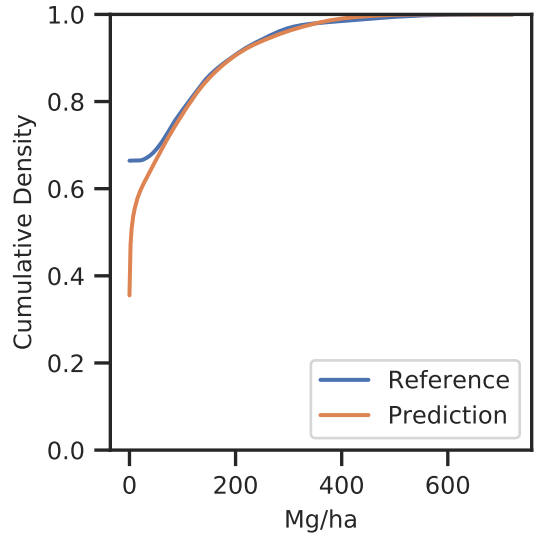


(b) Zero included

Ordinary frequency histogram (zone 8)



(a) Zero excluded



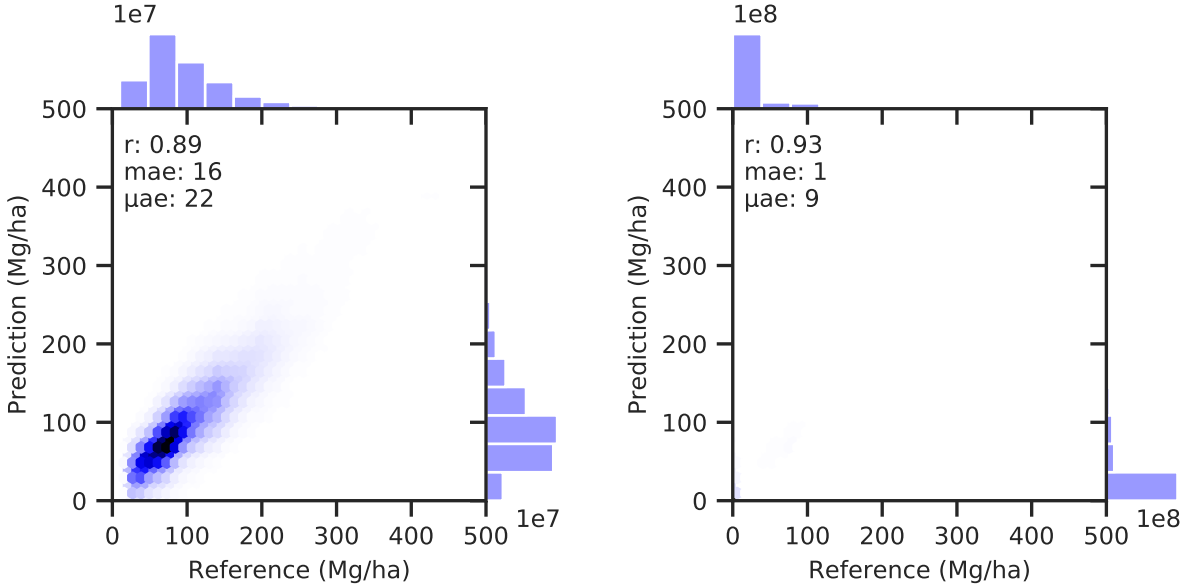
(b) Zero included

Cumulative density histogram (zone 8)

Return to zone table

Zone 9

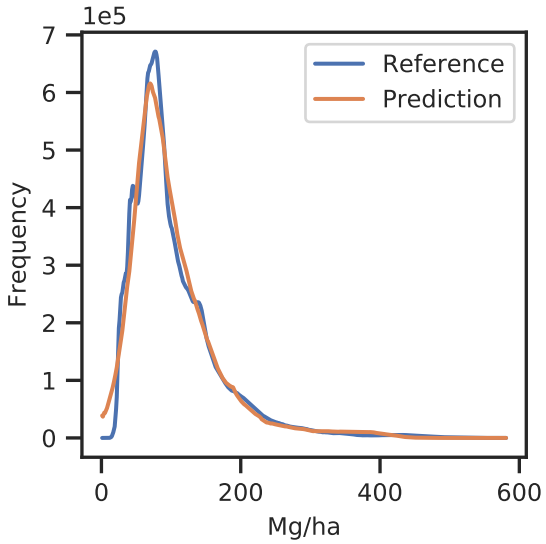
Zone map (zone 9)



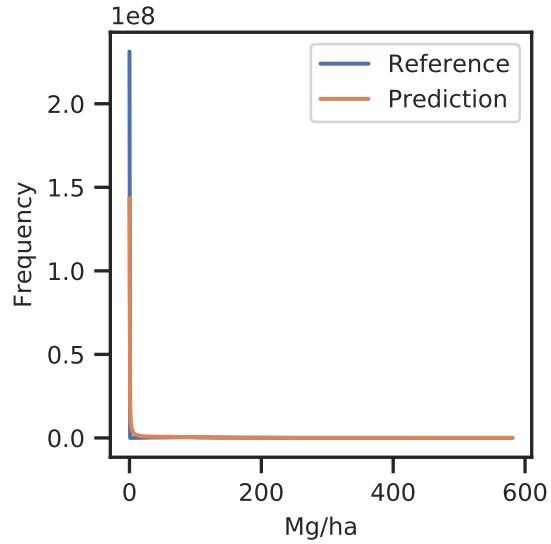
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 9)

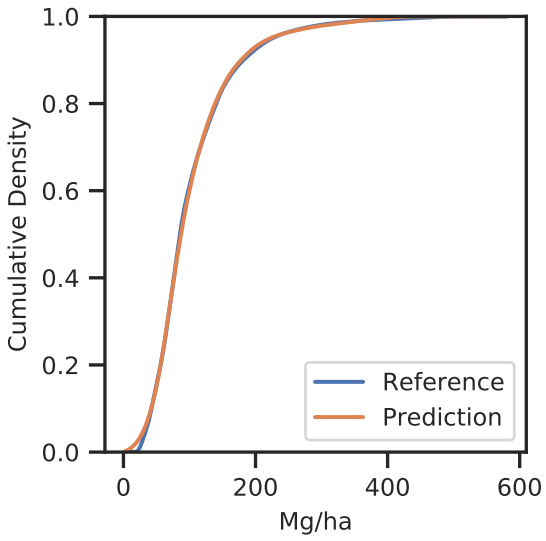


(a) Zero excluded

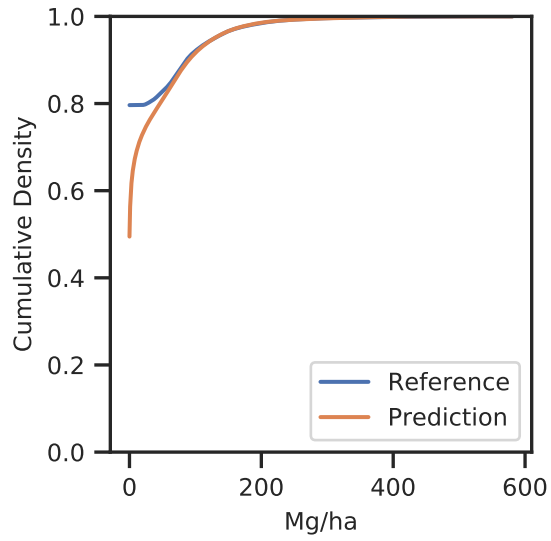


(b) Zero included

Ordinary frequency histogram (zone 9)



(a) Zero excluded



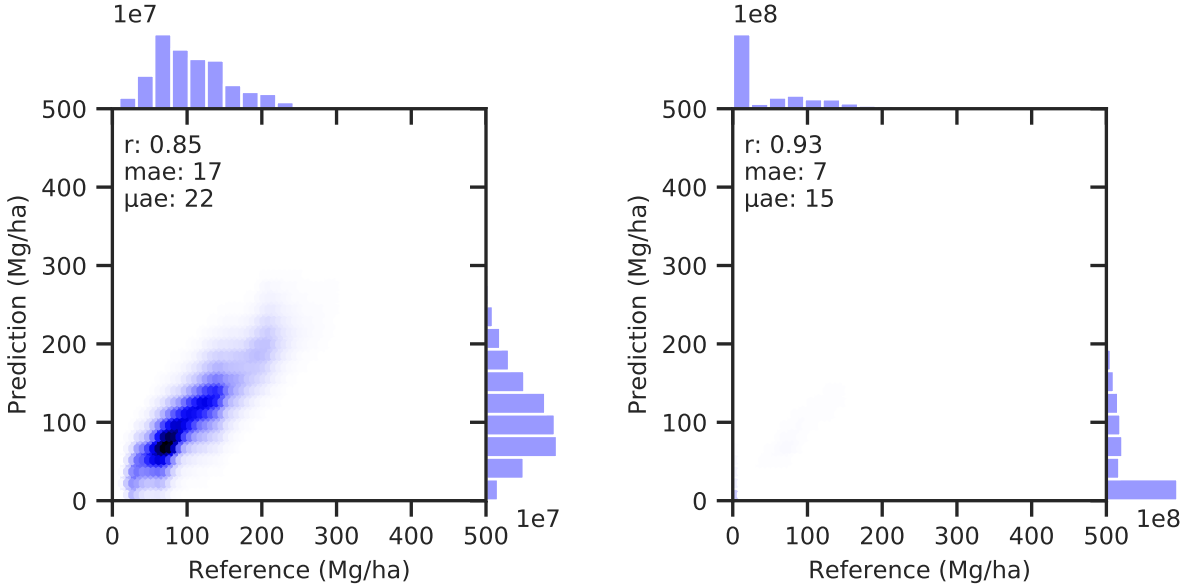
(b) Zero included

Cumulative density histogram (zone 9)

Return to zone table

Zone 10

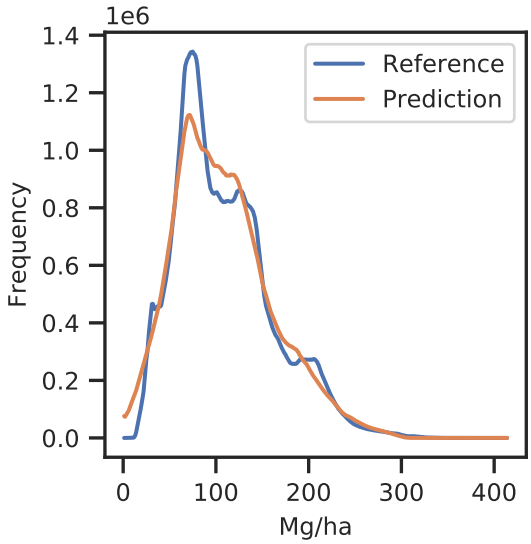
Zone map (zone 10)



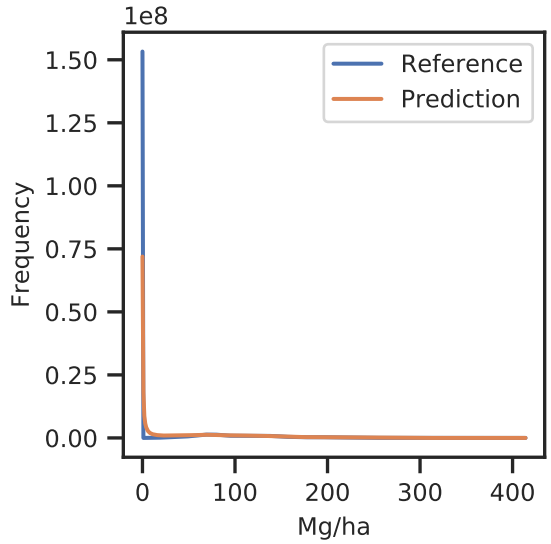
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 10)

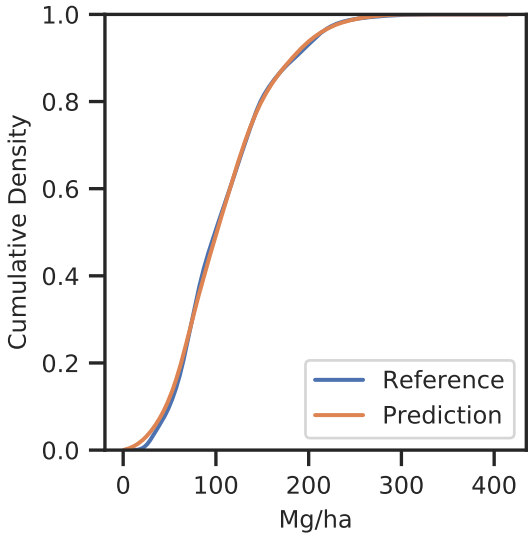


(a) Zero excluded

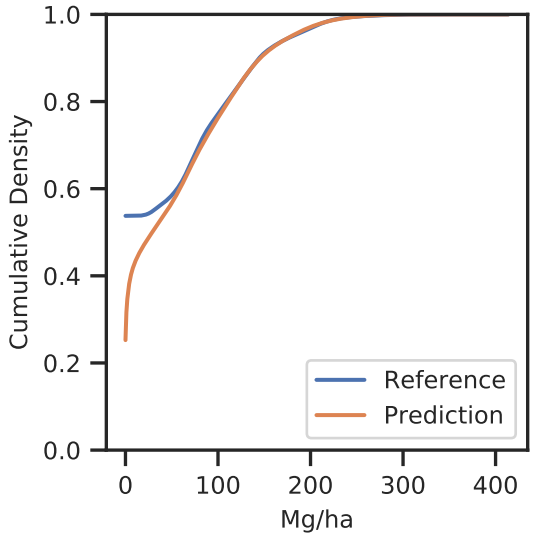


(b) Zero included

Ordinary frequency histogram (zone 10)



(a) Zero excluded



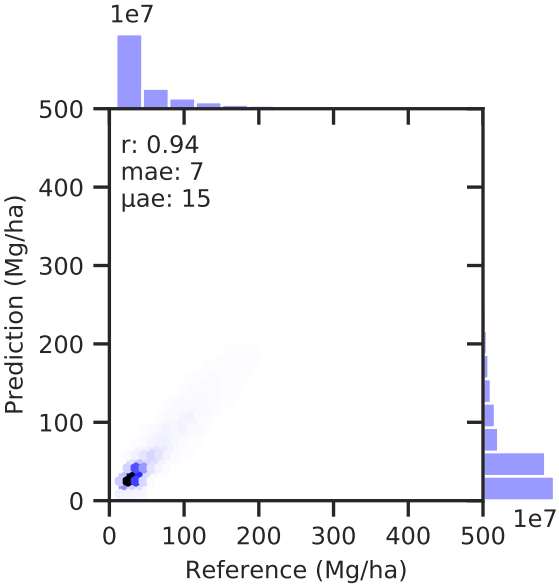
(b) Zero included

Cumulative density histogram (zone 10)

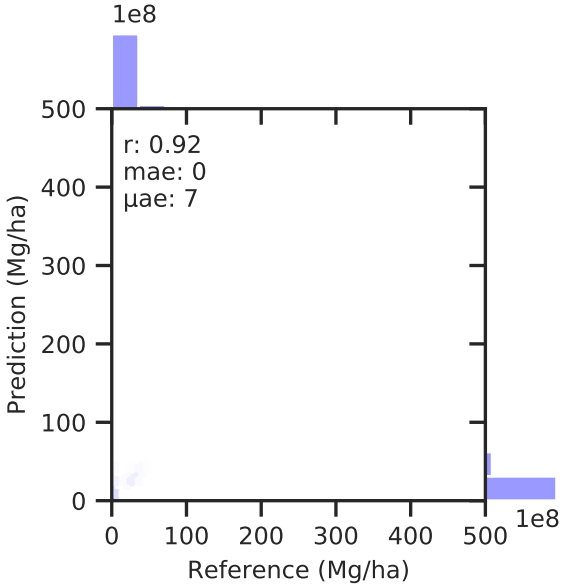
Return to zone table

Zone 12

Zone map (zone 12)

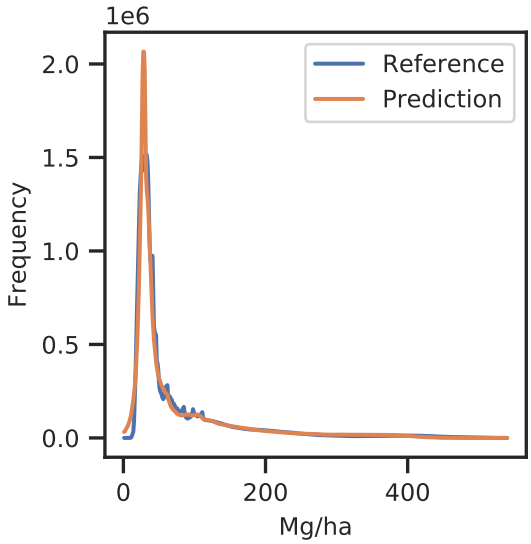


(a) Zero excluded

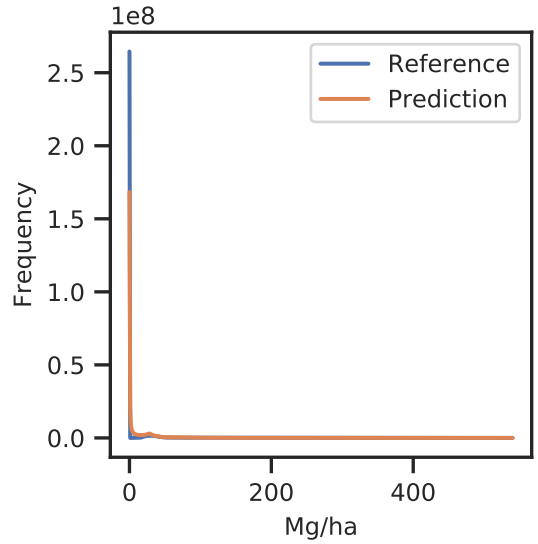


(b) Zero included

2-D frequency histogram (zone 12)

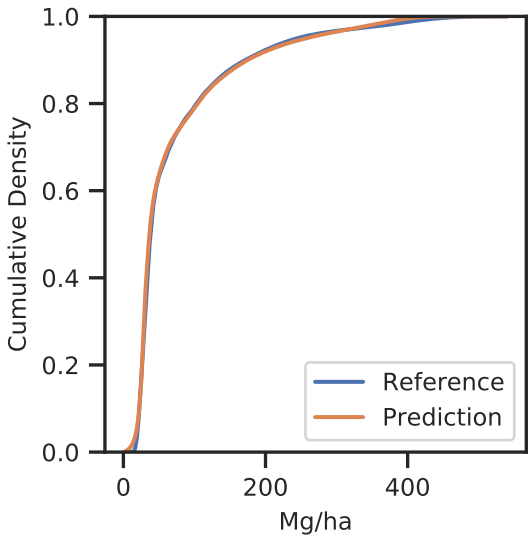


(a) Zero excluded

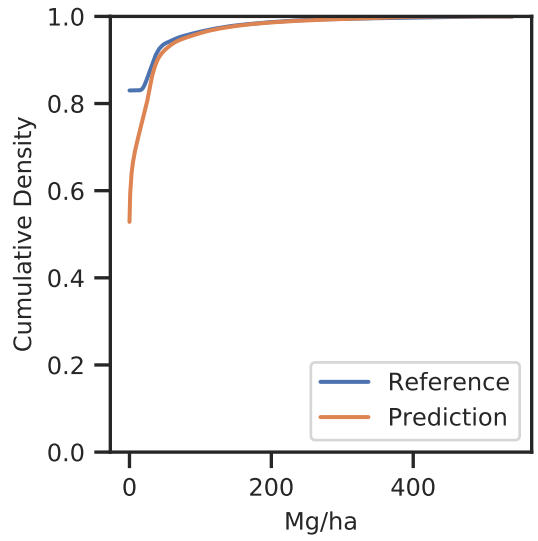


(b) Zero included

Ordinary frequency histogram (zone 12)



(a) Zero excluded



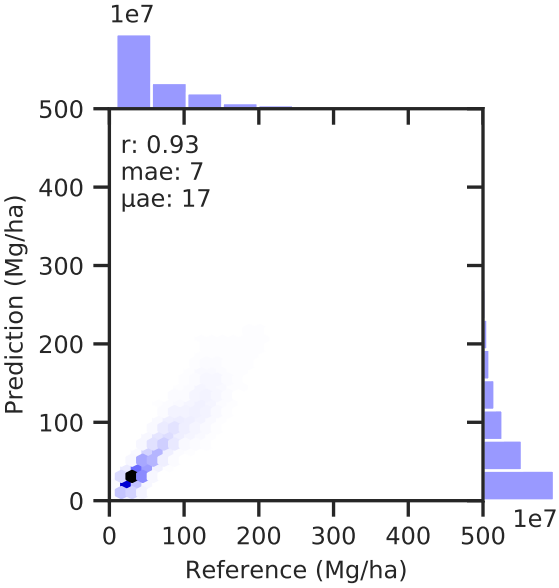
(b) Zero included

Cumulative density histogram (zone 12)

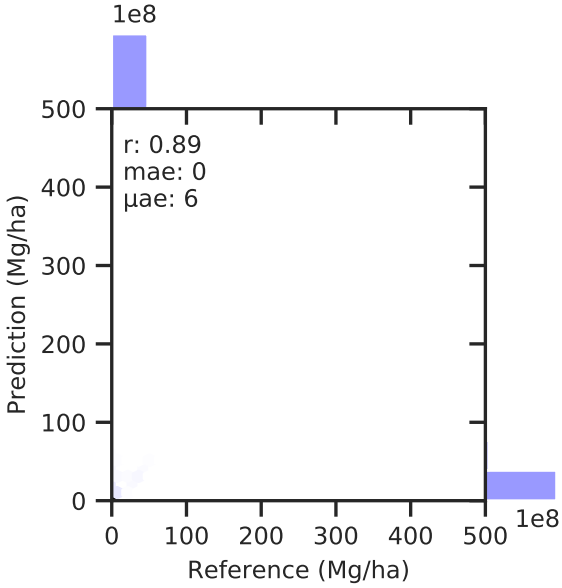
Return to zone table

Zone 13

Zone map (zone 13)

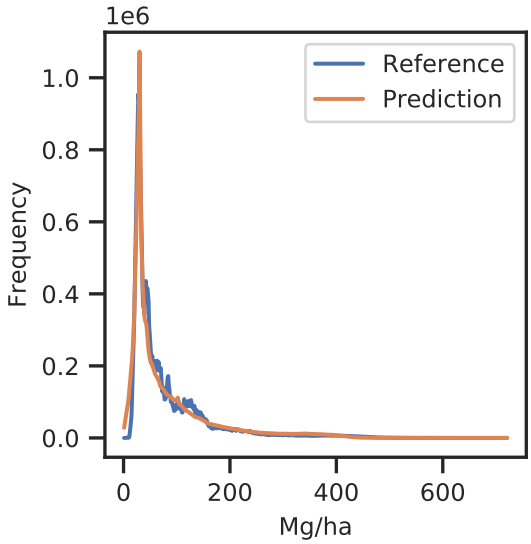


(a) Zero excluded

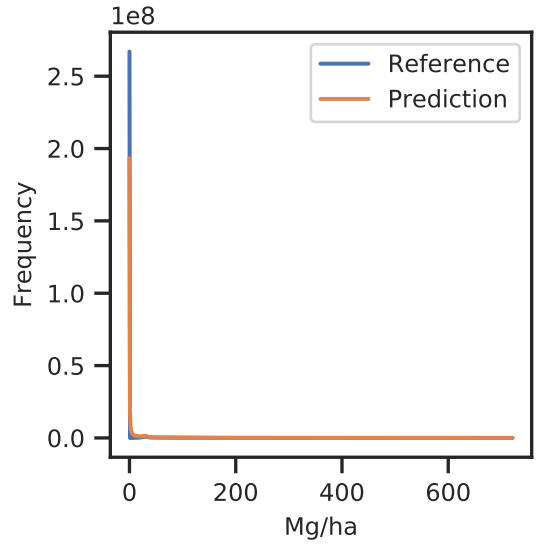


(b) Zero included

2-D frequency histogram (zone 13)

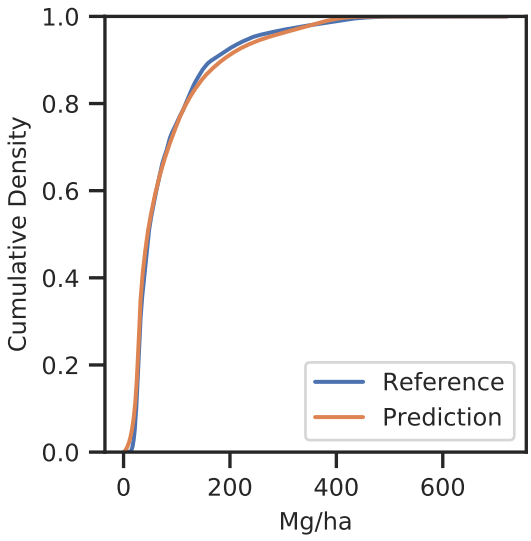


(a) Zero excluded

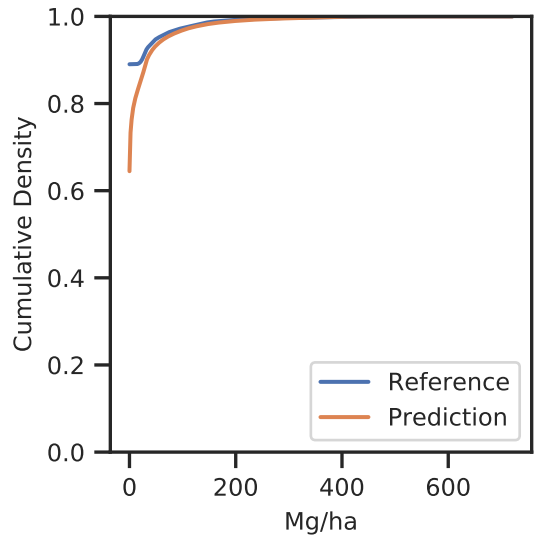


(b) Zero included

Ordinary frequency histogram (zone 13)



(a) Zero excluded



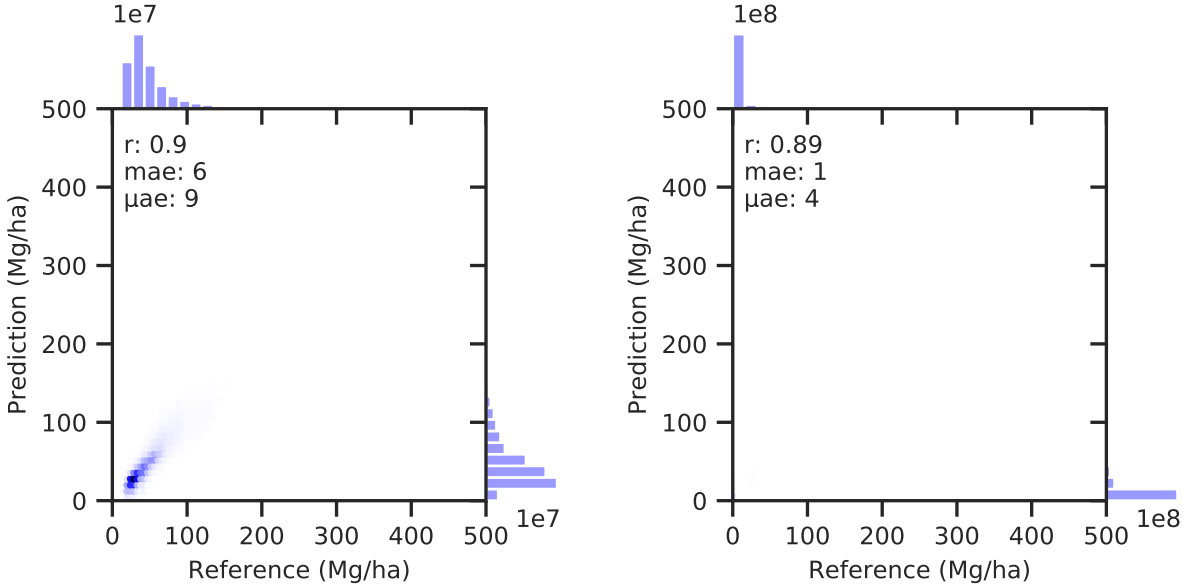
(b) Zero included

Cumulative density histogram (zone 13)

Return to zone table

Zone 14

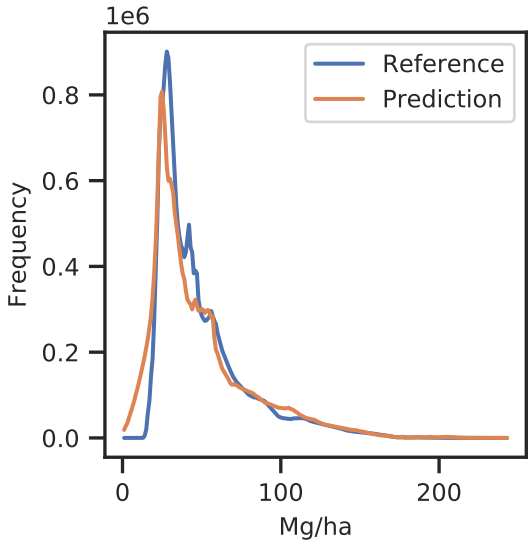
Zone map (zone 14)



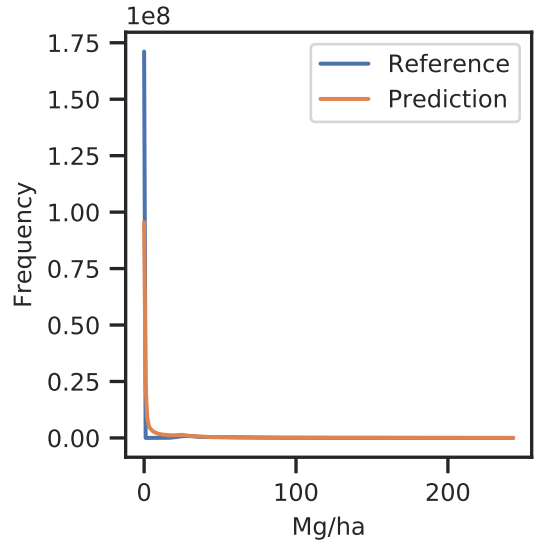
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 14)

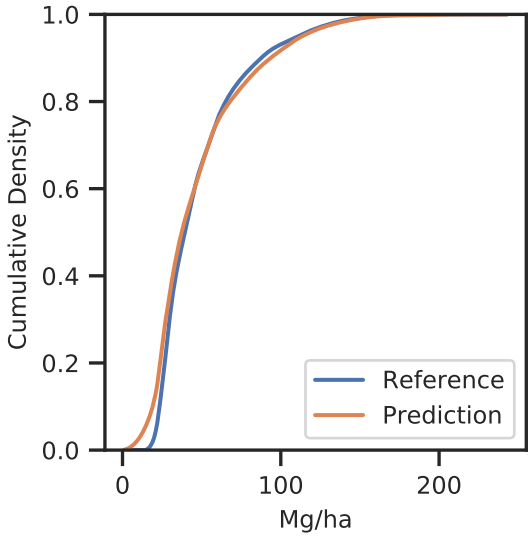


(a) Zero excluded

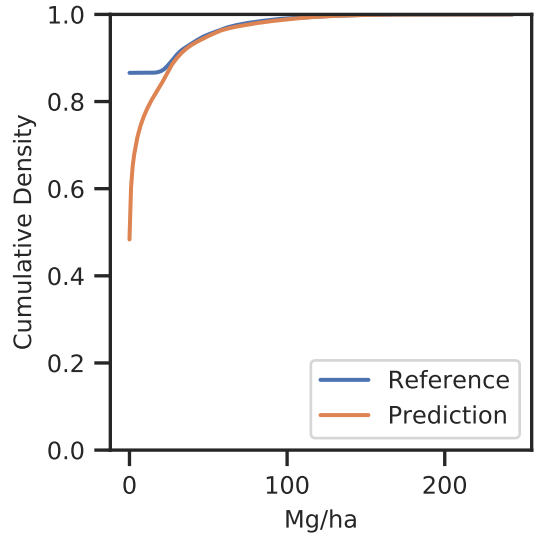


(b) Zero included

Ordinary frequency histogram (zone 14)



(a) Zero excluded



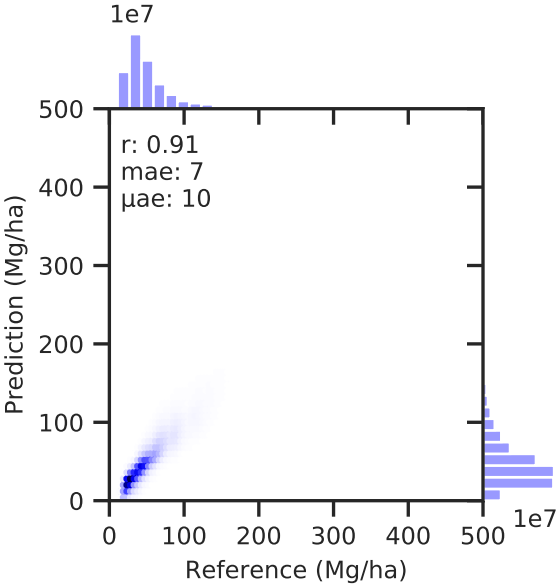
(b) Zero included

Cumulative density histogram (zone 14)

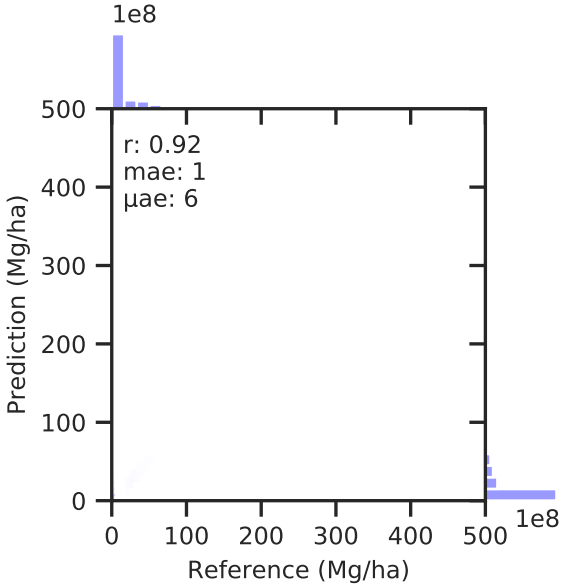
Return to zone table

Zone 15

Zone map (zone 15)

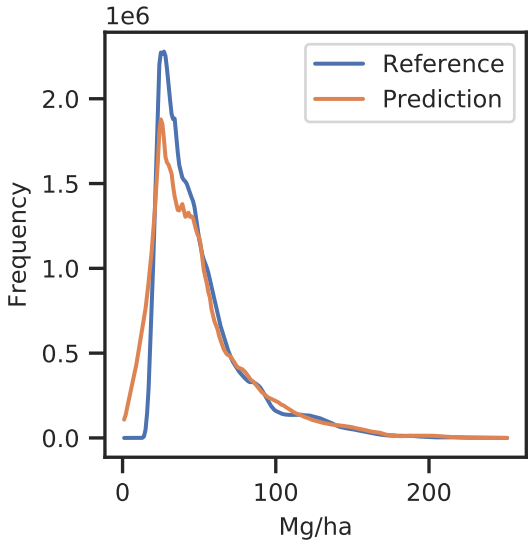


(a) Zero excluded

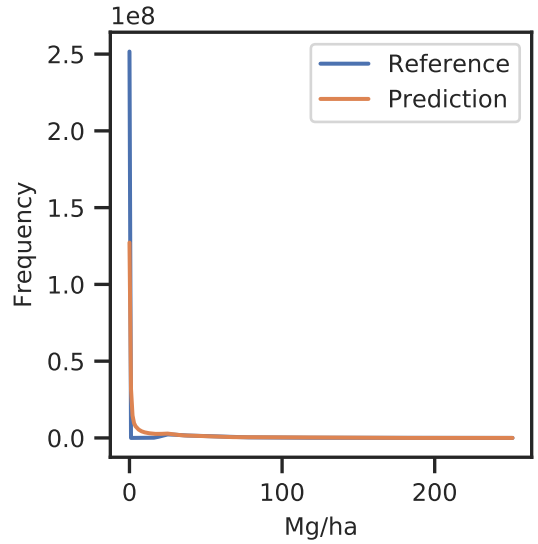


(b) Zero included

2-D frequency histogram (zone 15)

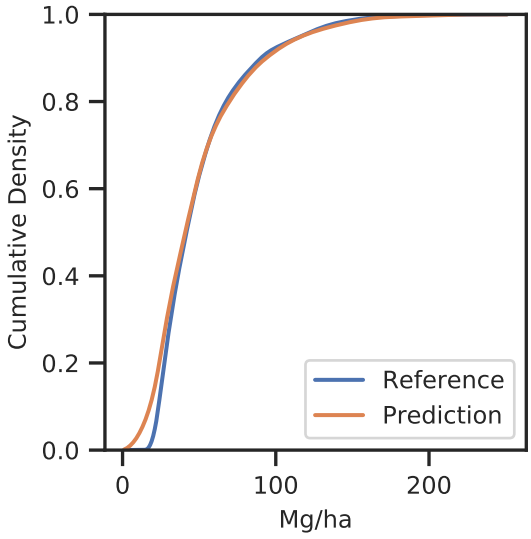


(a) Zero excluded

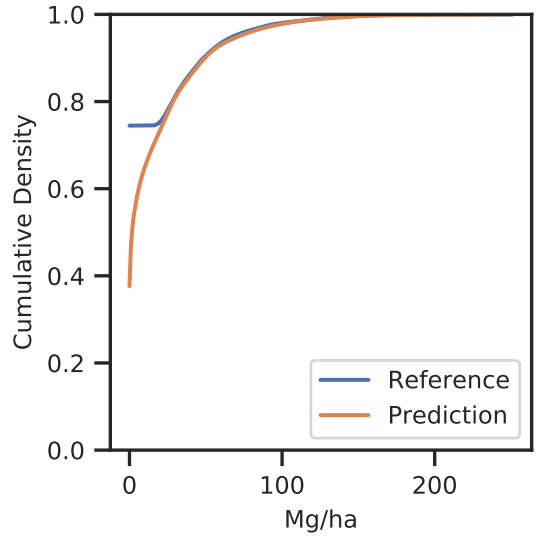


(b) Zero included

Ordinary frequency histogram (zone 15)



(a) Zero excluded



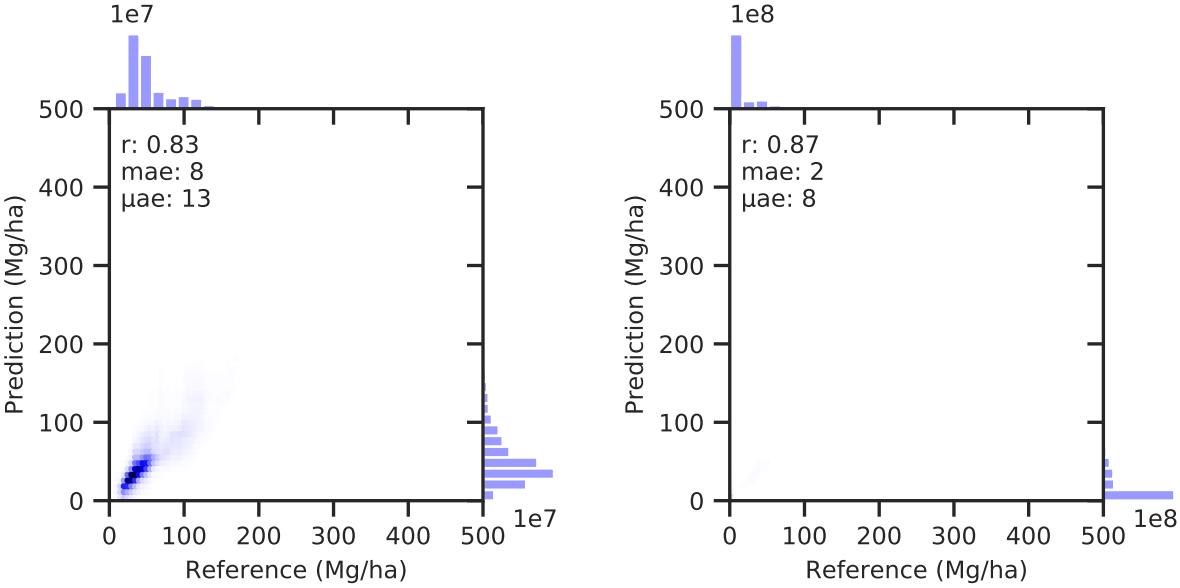
(b) Zero included

Cumulative density histogram (zone 15)

Return to zone table

Zone 16

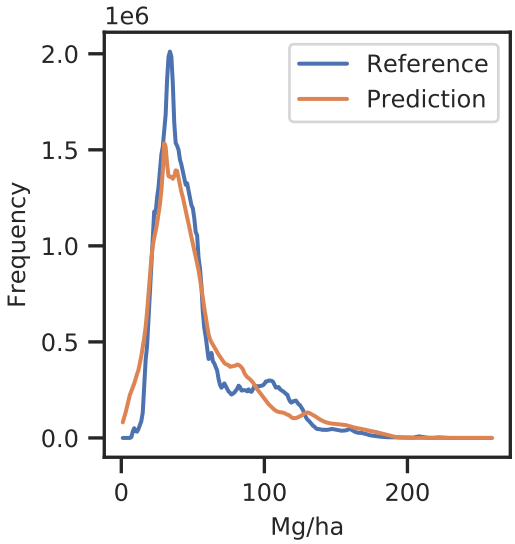
Zone map (zone 16)



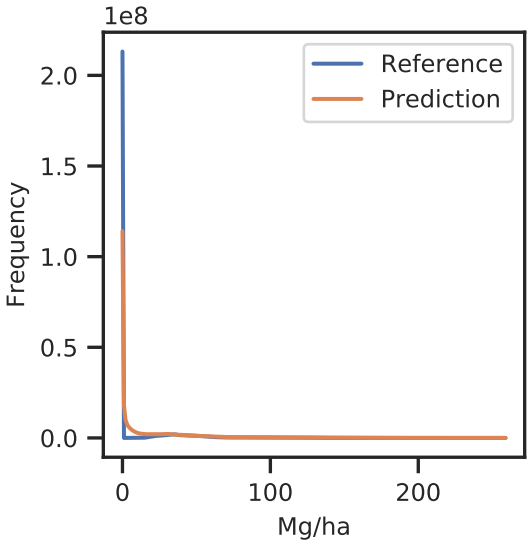
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 16)

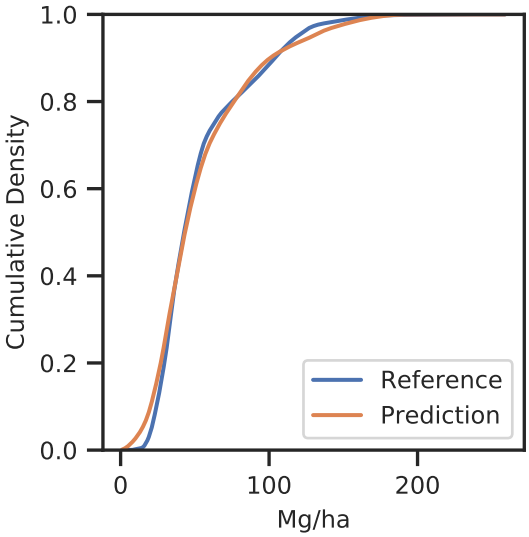


(a) Zero excluded

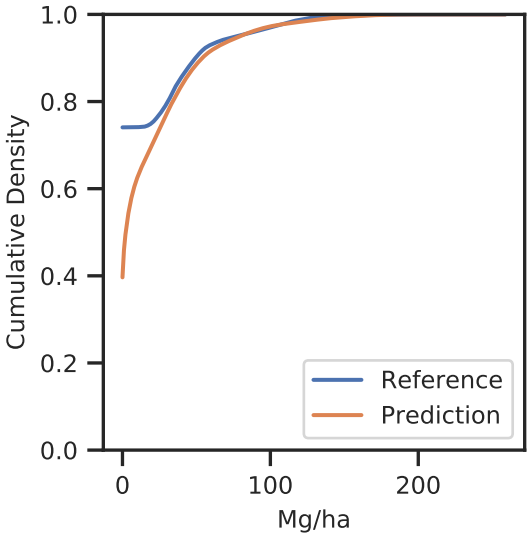


(b) Zero included

Ordinary frequency histogram (zone 16)



(a) Zero excluded



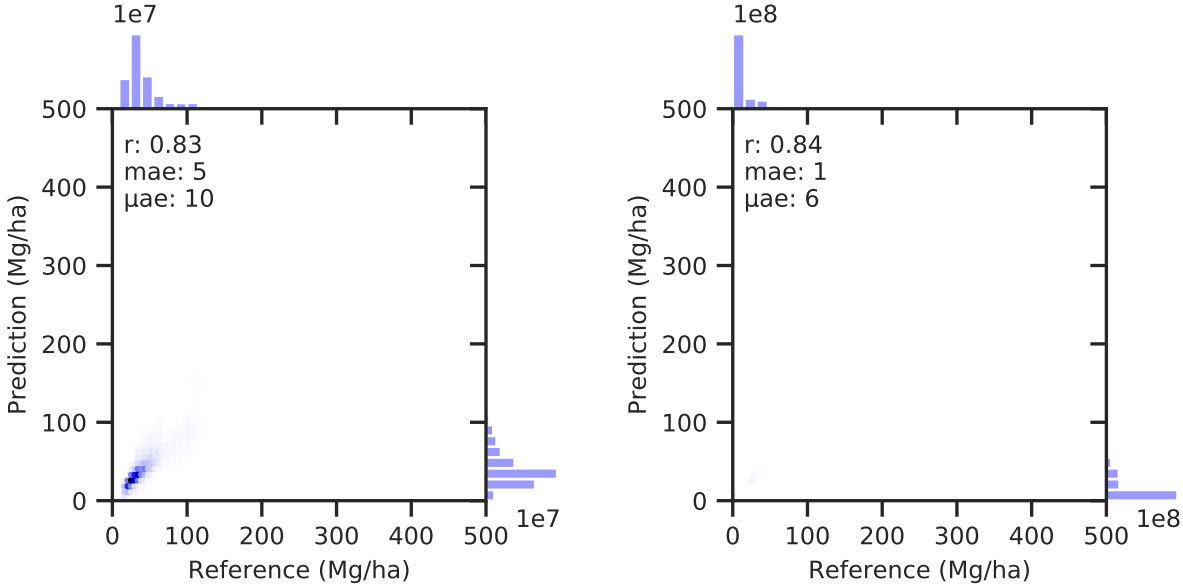
(b) Zero included

Cumulative density histogram (zone 16)

Return to zone table

Zone 17

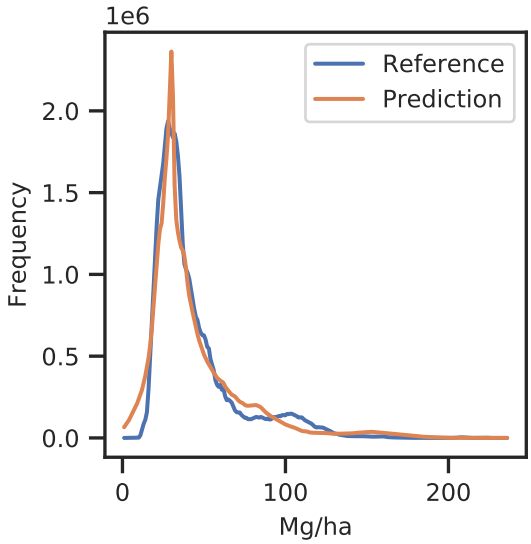
Zone map (zone 17)



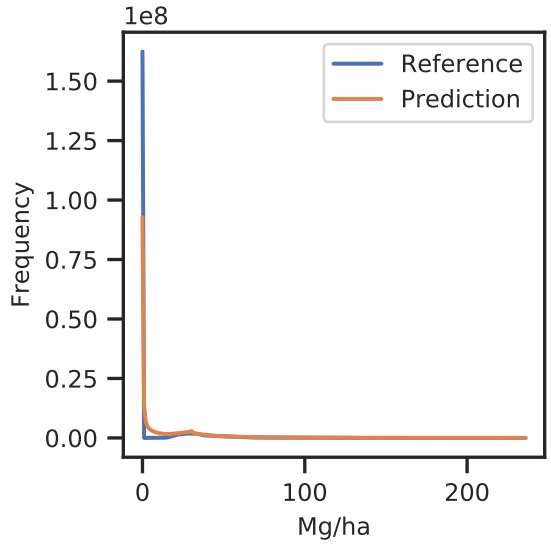
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 17)

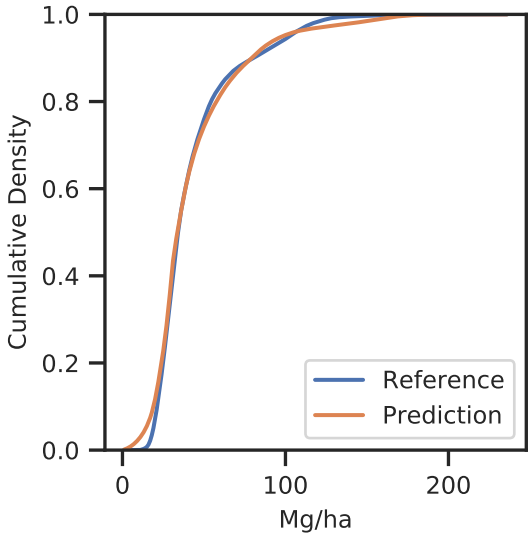


(a) Zero excluded

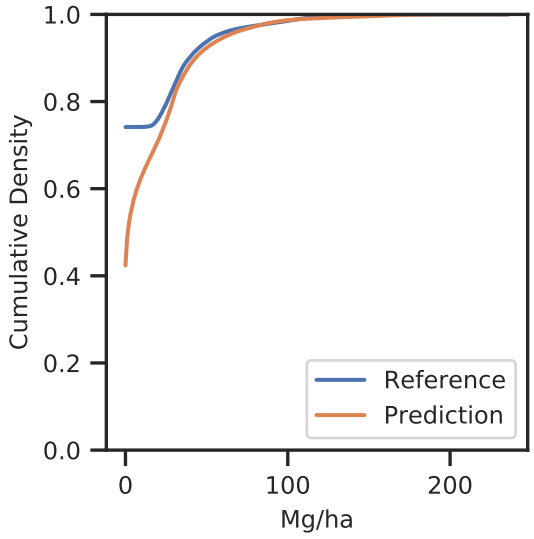


(b) Zero included

Ordinary frequency histogram (zone 17)



(a) Zero excluded



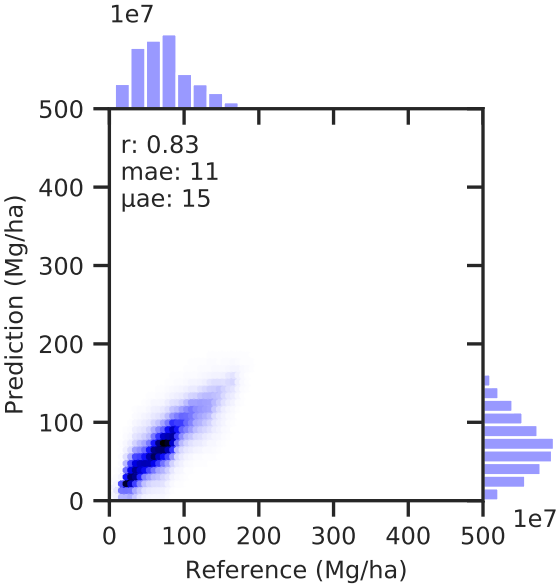
(b) Zero included

Cumulative density histogram (zone 17)

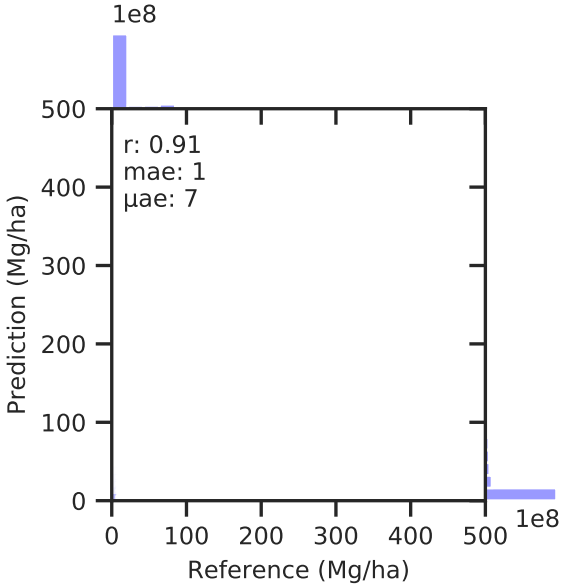
Return to zone table

Zone 18

Zone map (zone 18)

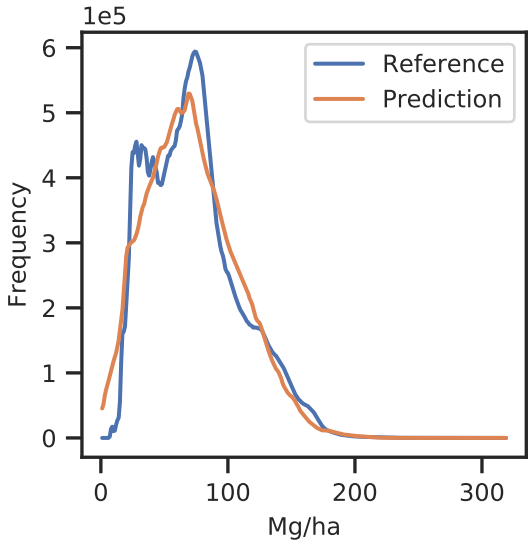


(a) Zero excluded

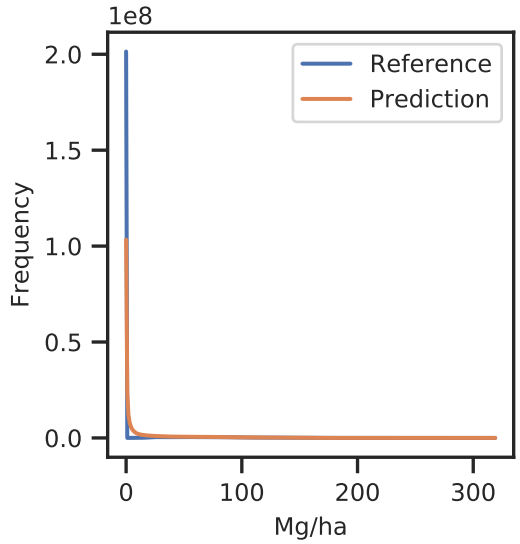


(b) Zero included

2-D frequency histogram (zone 18)

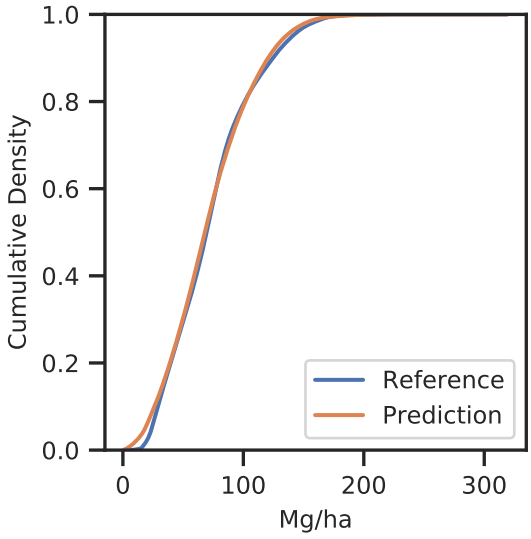


(a) Zero excluded

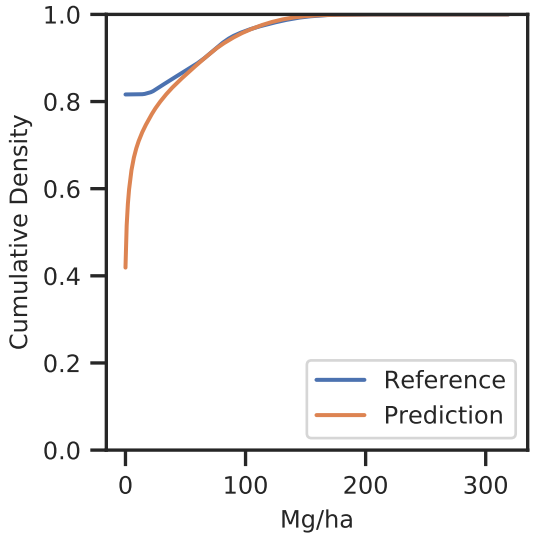


(b) Zero included

Ordinary frequency histogram (zone 18)



(a) Zero excluded

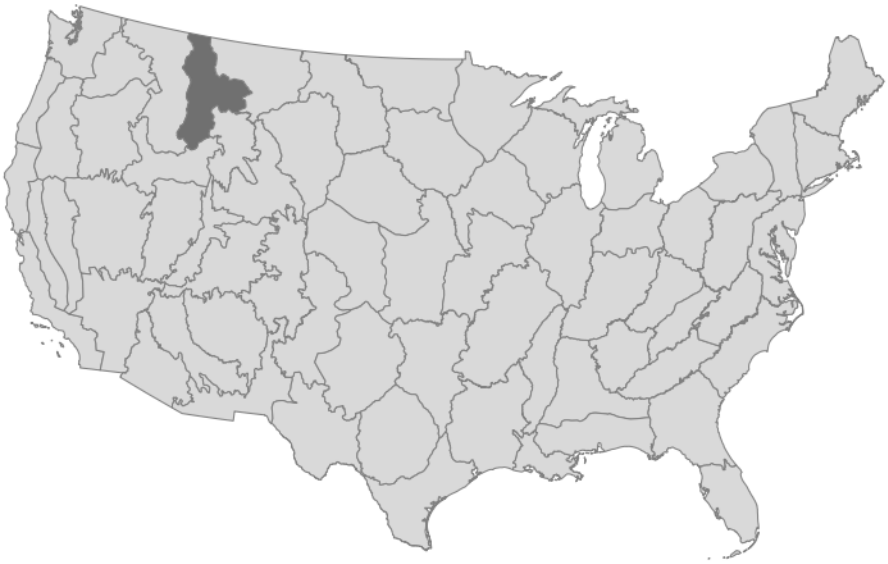


(b) Zero included

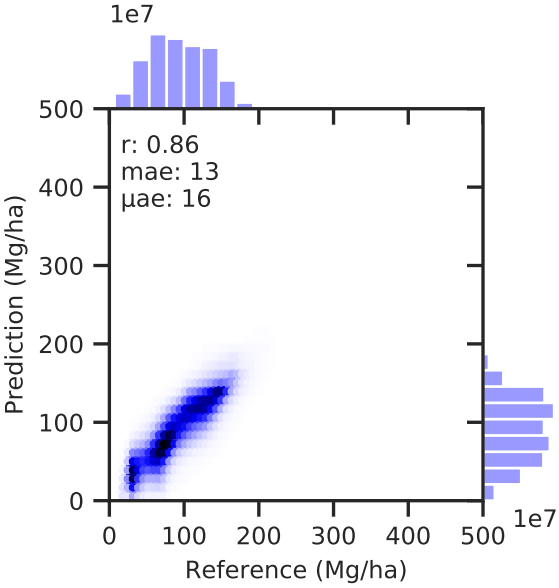
Cumulative density histogram (zone 18)

Return to zone table

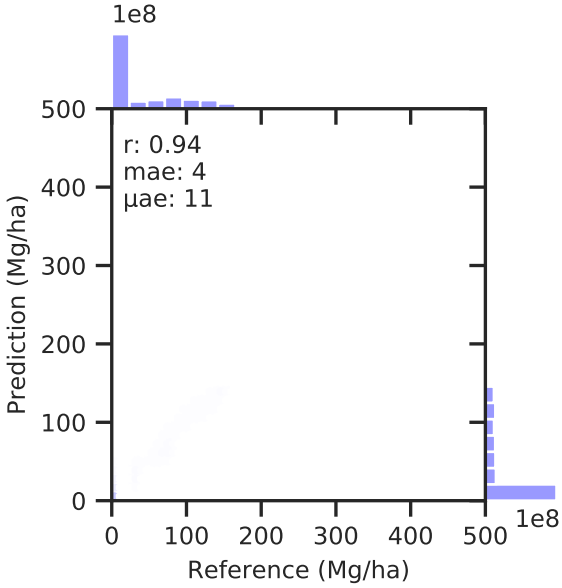
Zone 19



Zone map (zone 19)

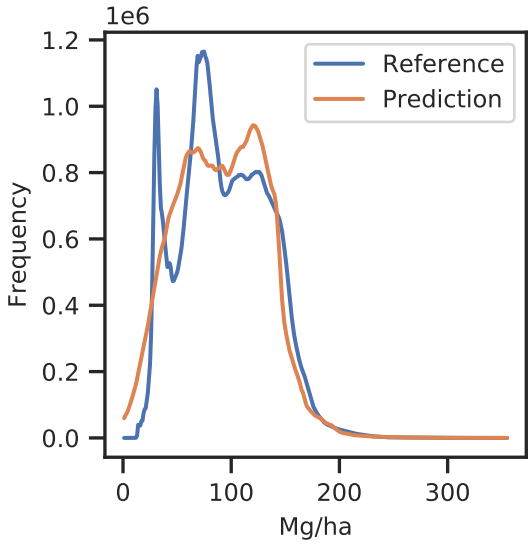


(a) Zero excluded

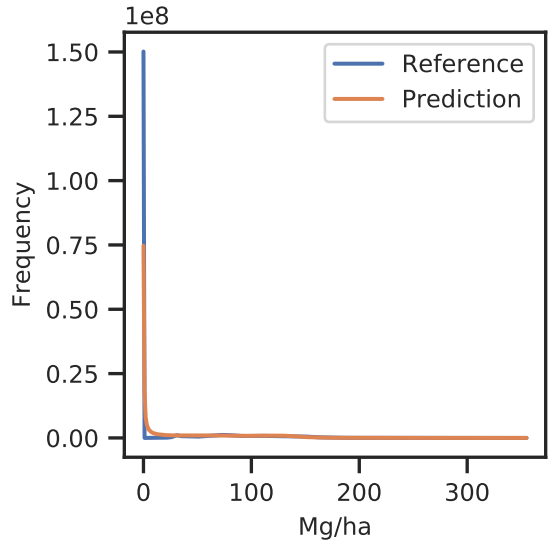


(b) Zero included

2-D frequency histogram (zone 19)

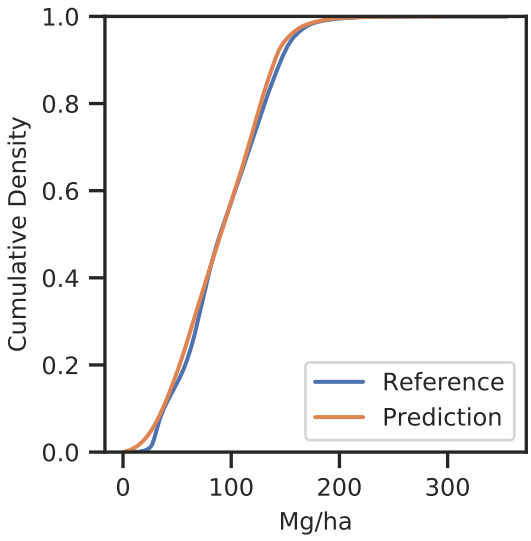


(a) Zero excluded

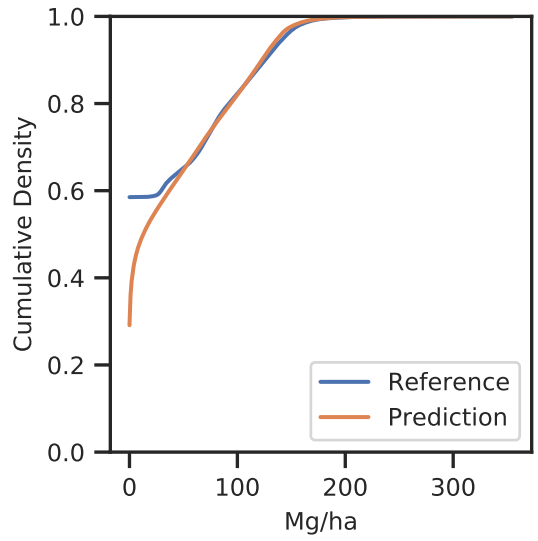


(b) Zero included

Ordinary frequency histogram (zone 19)



(a) Zero excluded



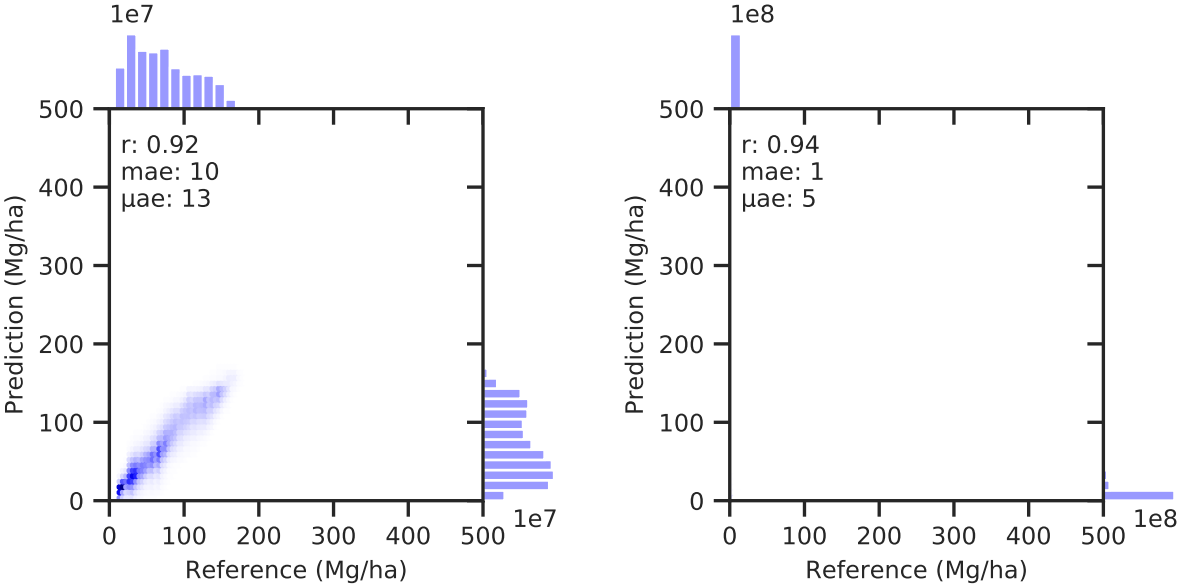
(b) Zero included

Cumulative density histogram (zone 19)

Return to zone table

Zone 20

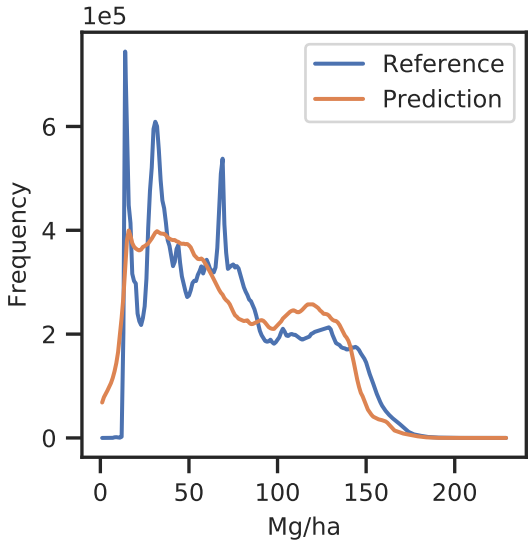
Zone map (zone 20)



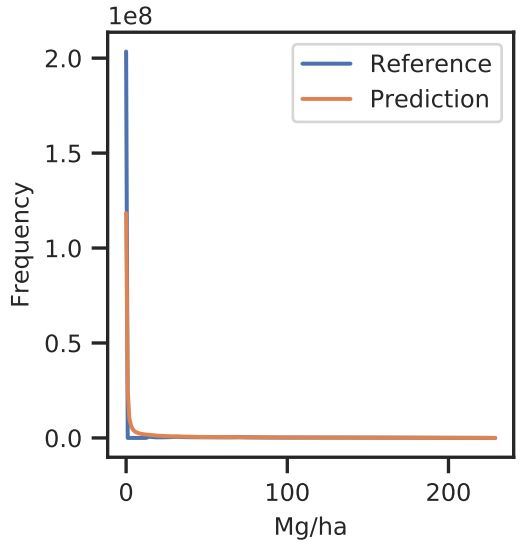
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 20)

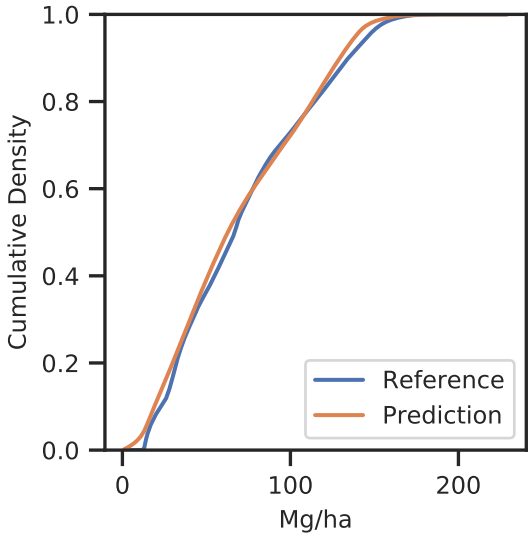


(a) Zero excluded

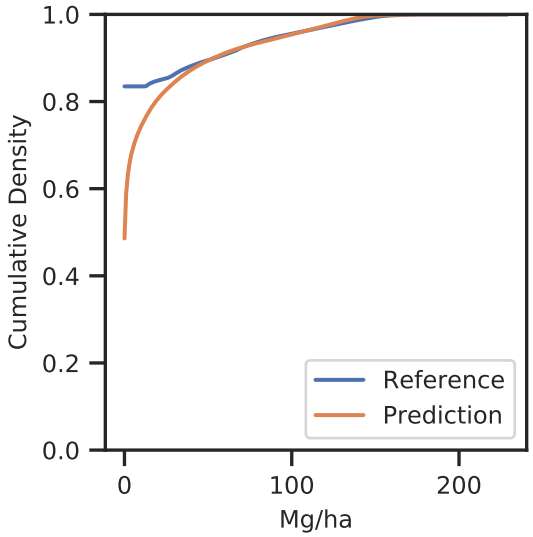


(b) Zero included

Ordinary frequency histogram (zone 20)



(a) Zero excluded



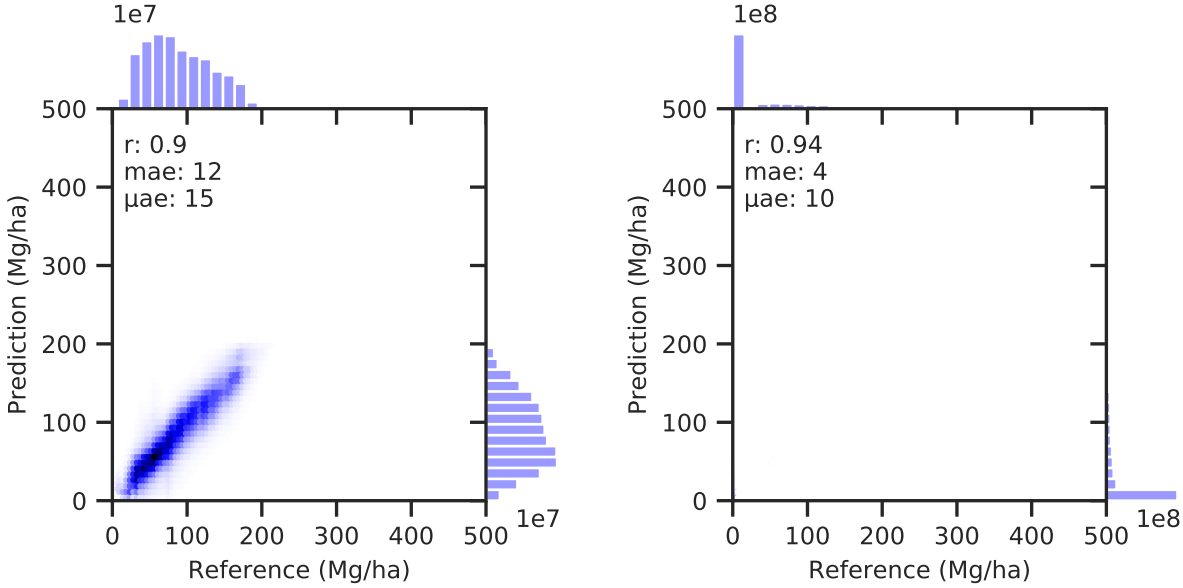
(b) Zero included

Cumulative density histogram (zone 20)

Return to zone table

Zone 21

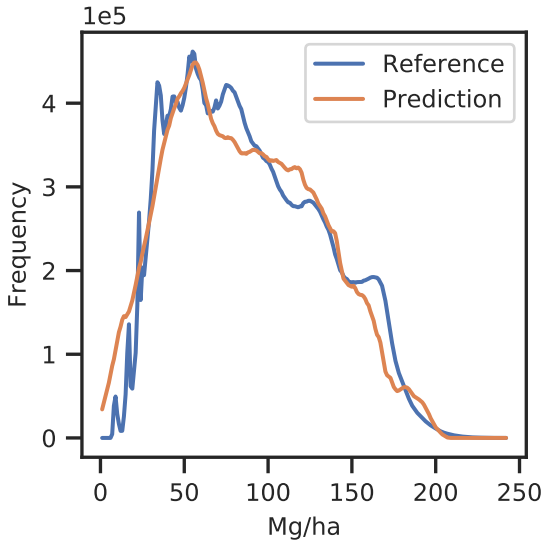
Zone map (zone 21)



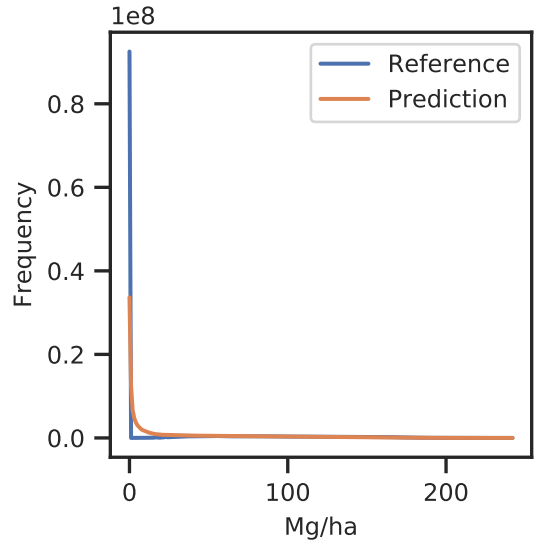
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 21)

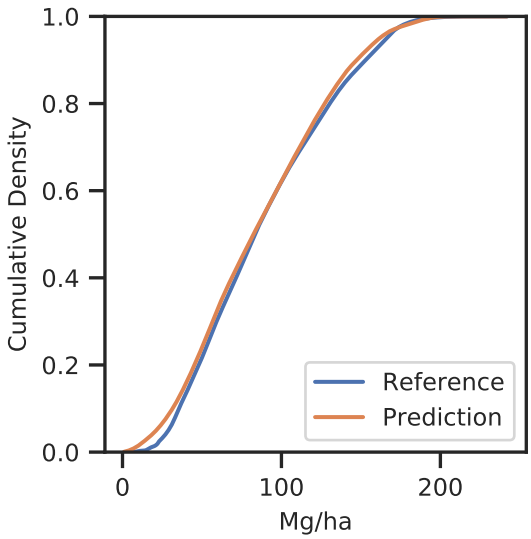


(a) Zero excluded

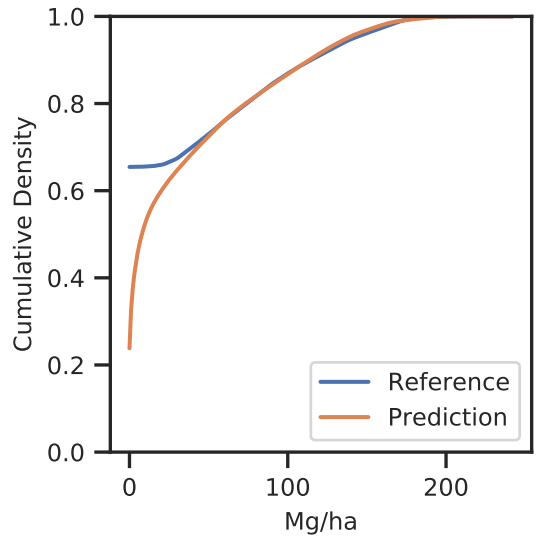


(b) Zero included

Ordinary frequency histogram (zone 21)



(a) Zero excluded



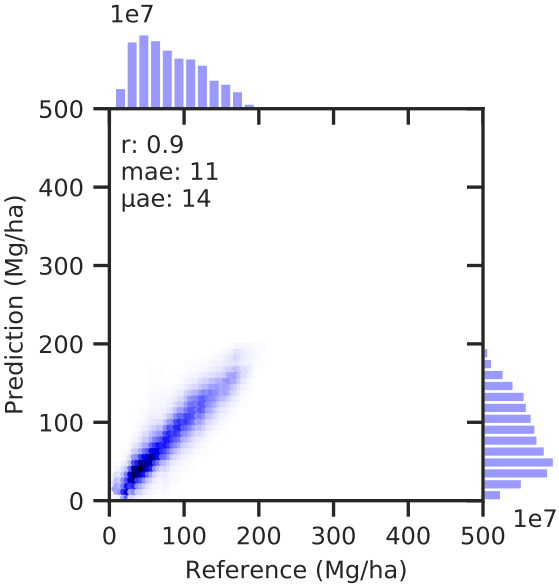
(b) Zero included

Cumulative density histogram (zone 21)

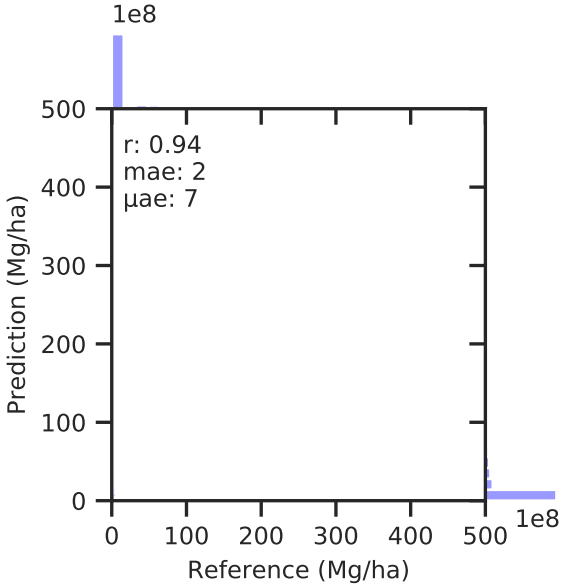
Return to zone table

Zone 22

Zone map (zone 22)

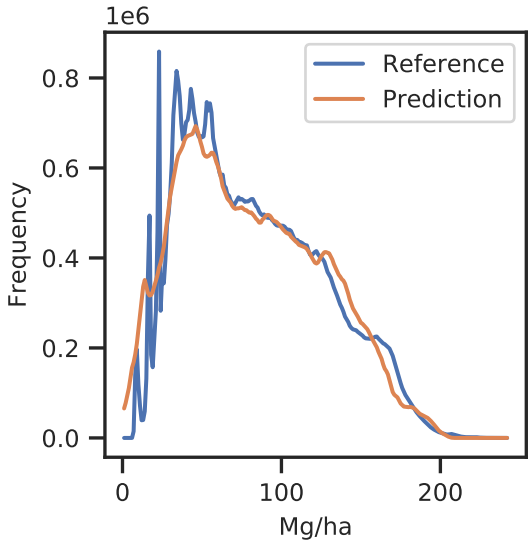


(a) Zero excluded

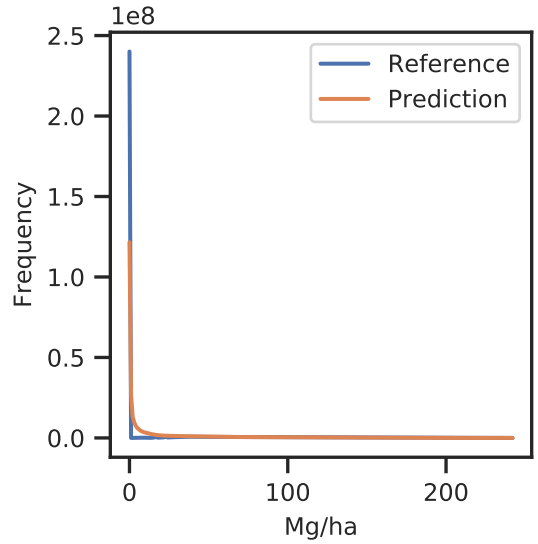


(b) Zero included

2-D frequency histogram (zone 22)

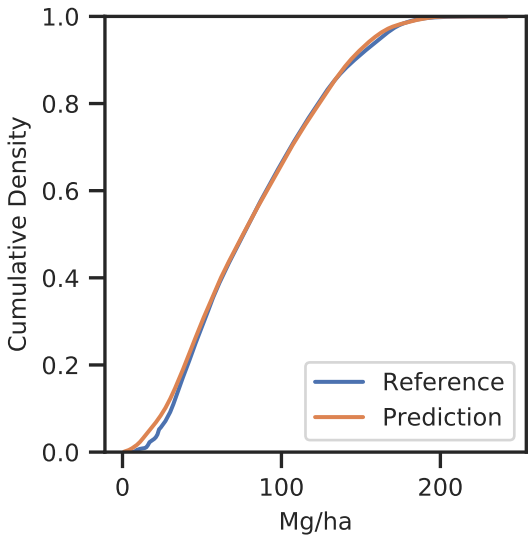


(a) Zero excluded

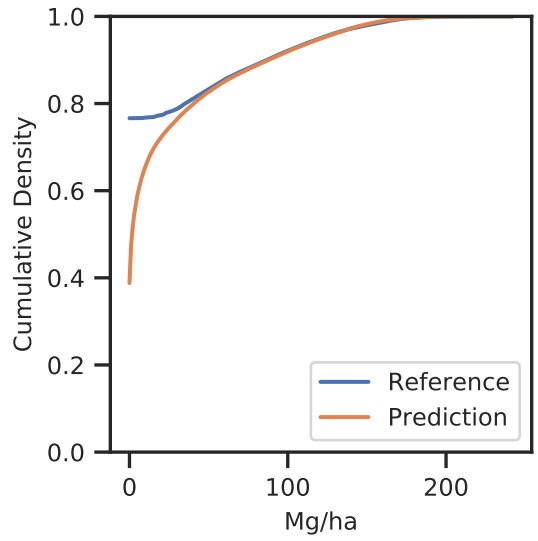


(b) Zero included

Ordinary frequency histogram (zone 22)



(a) Zero excluded



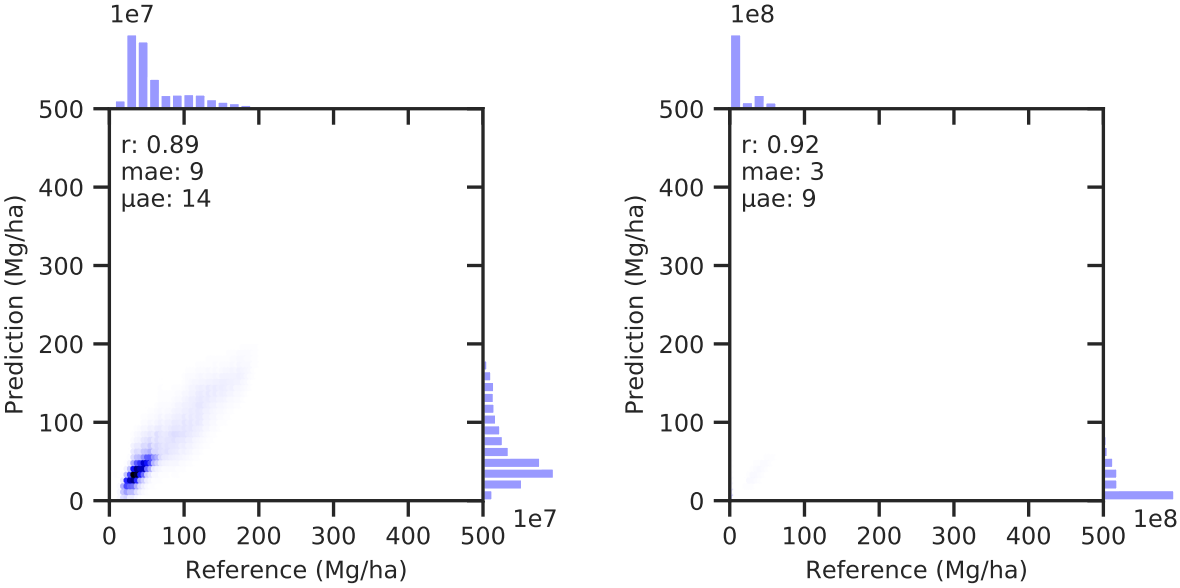
(b) Zero included

Cumulative density histogram (zone 22)

Return to zone table

Zone 23

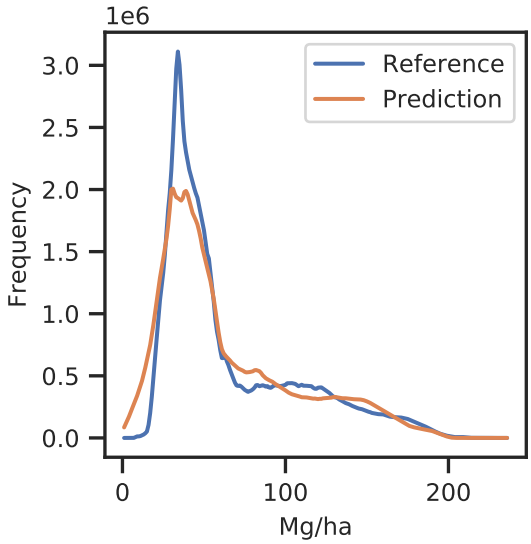
Zone map (zone 23)



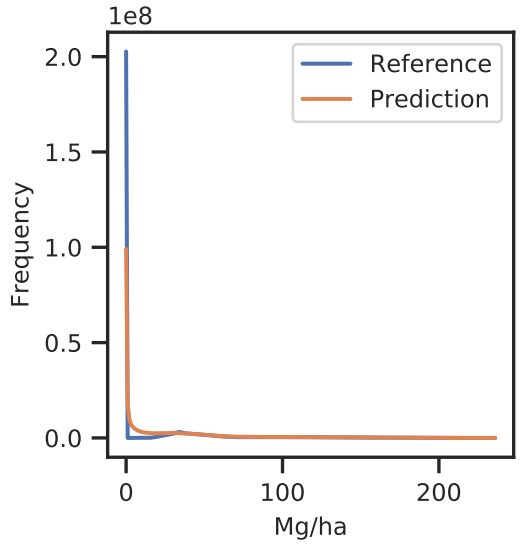
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 23)

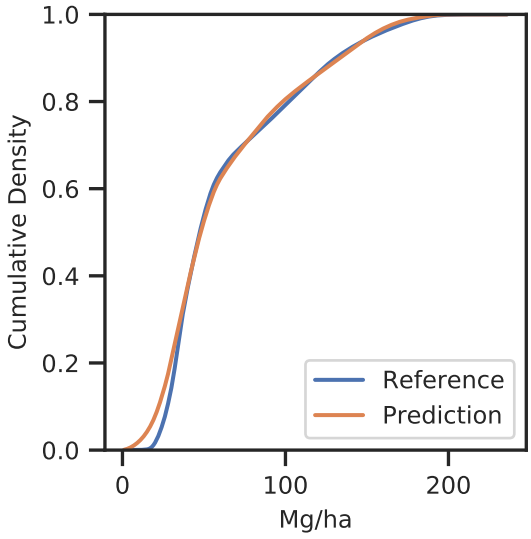


(a) Zero excluded

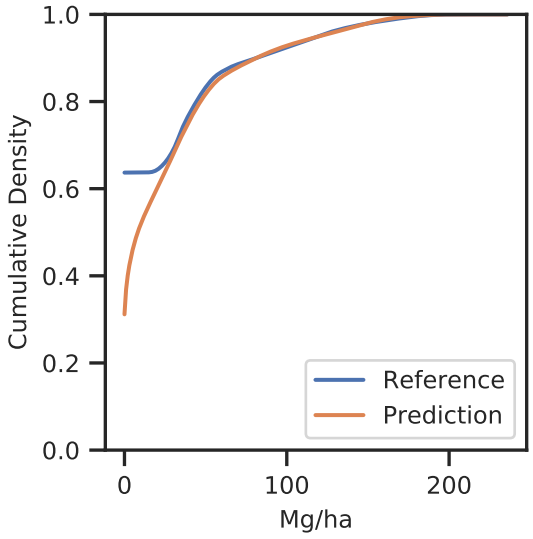


(b) Zero included

Ordinary frequency histogram (zone 23)



(a) Zero excluded



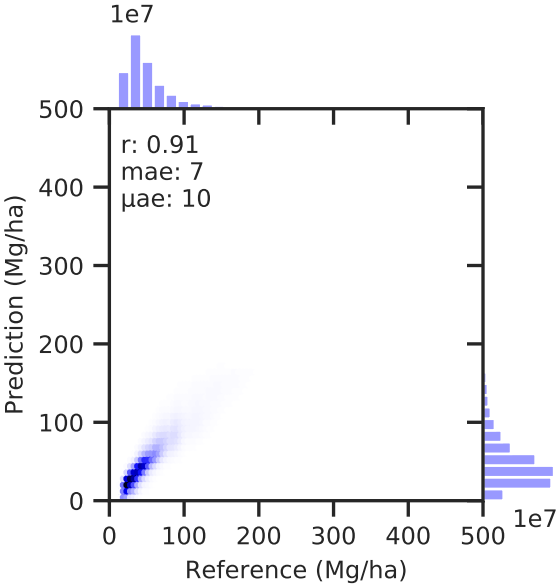
(b) Zero included

Cumulative density histogram (zone 23)

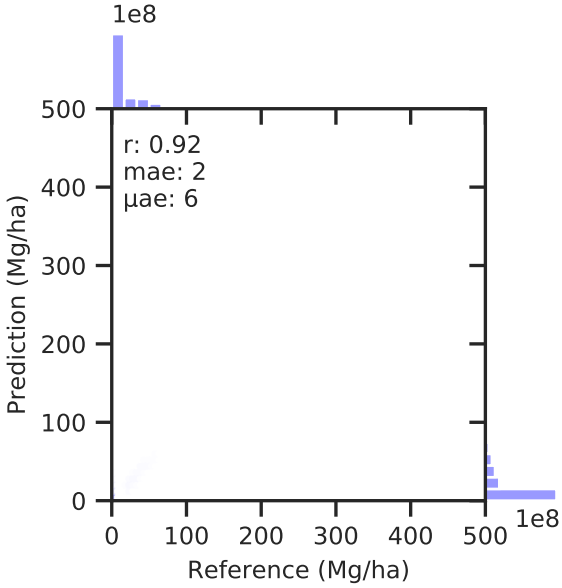
Return to zone table

Zone 24

Zone map (zone 24)

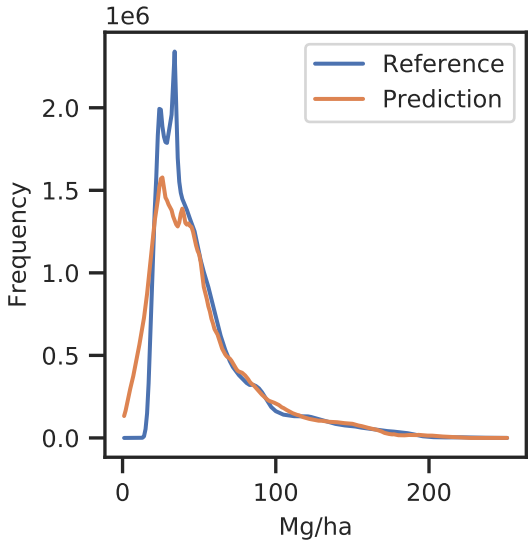


(a) Zero excluded

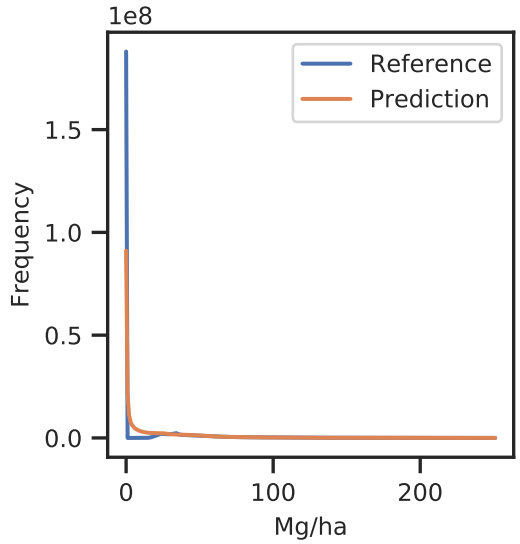


(b) Zero included

2-D frequency histogram (zone 24)

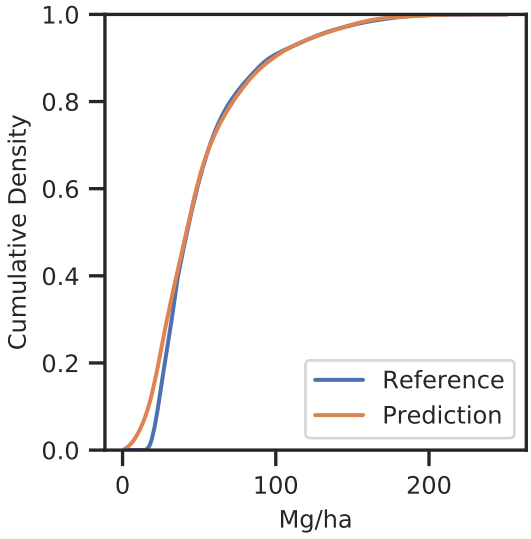


(a) Zero excluded

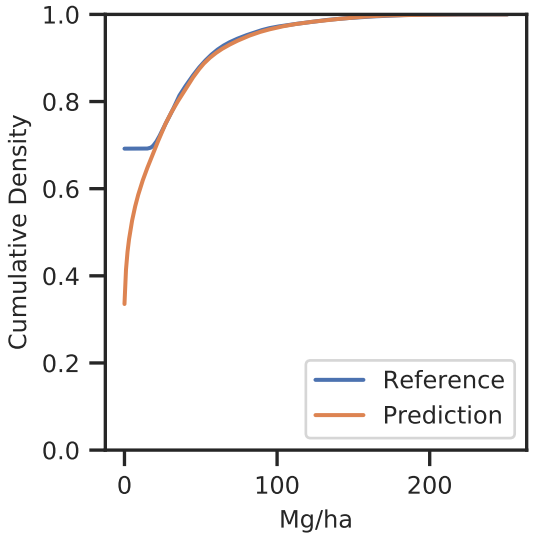


(b) Zero included

Ordinary frequency histogram (zone 24)



(a) Zero excluded



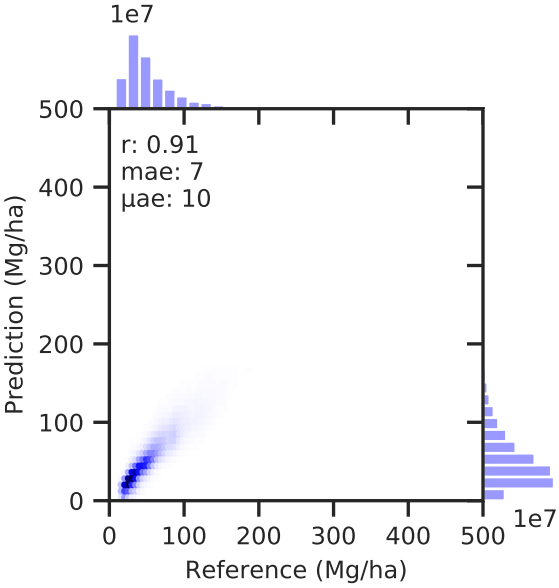
(b) Zero included

Cumulative density histogram (zone 24)

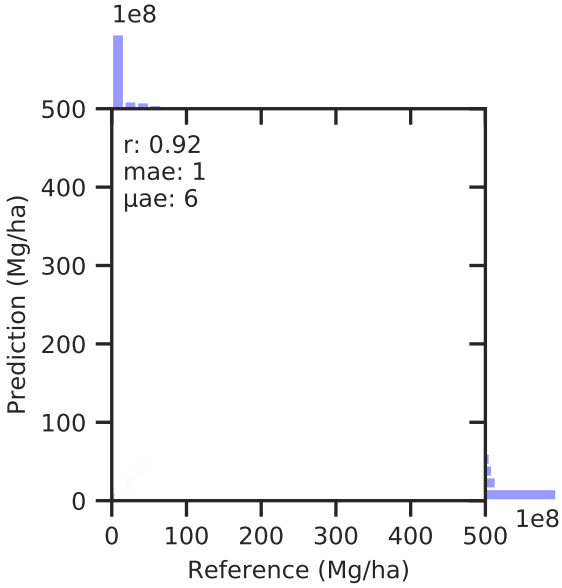
Return to zone table

Zone 25

Zone map (zone 25)

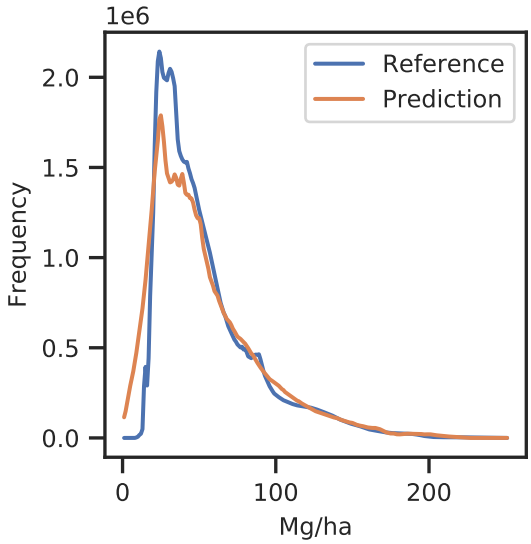


(a) Zero excluded

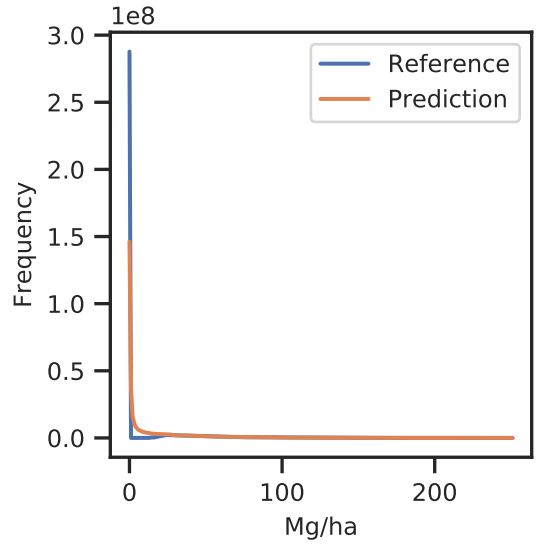


(b) Zero included

2-D frequency histogram (zone 25)

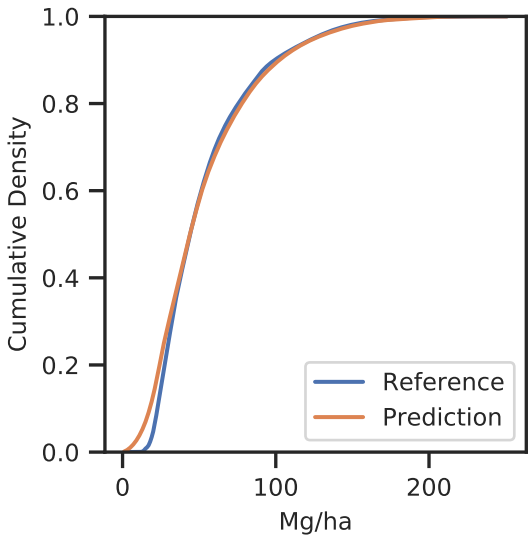


(a) Zero excluded

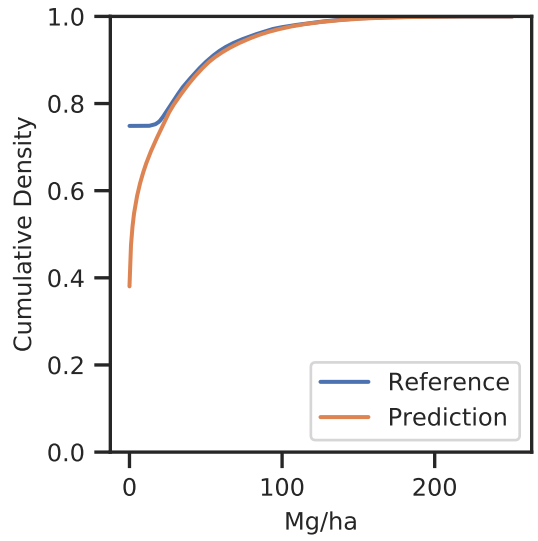


(b) Zero included

Ordinary frequency histogram (zone 25)



(a) Zero excluded



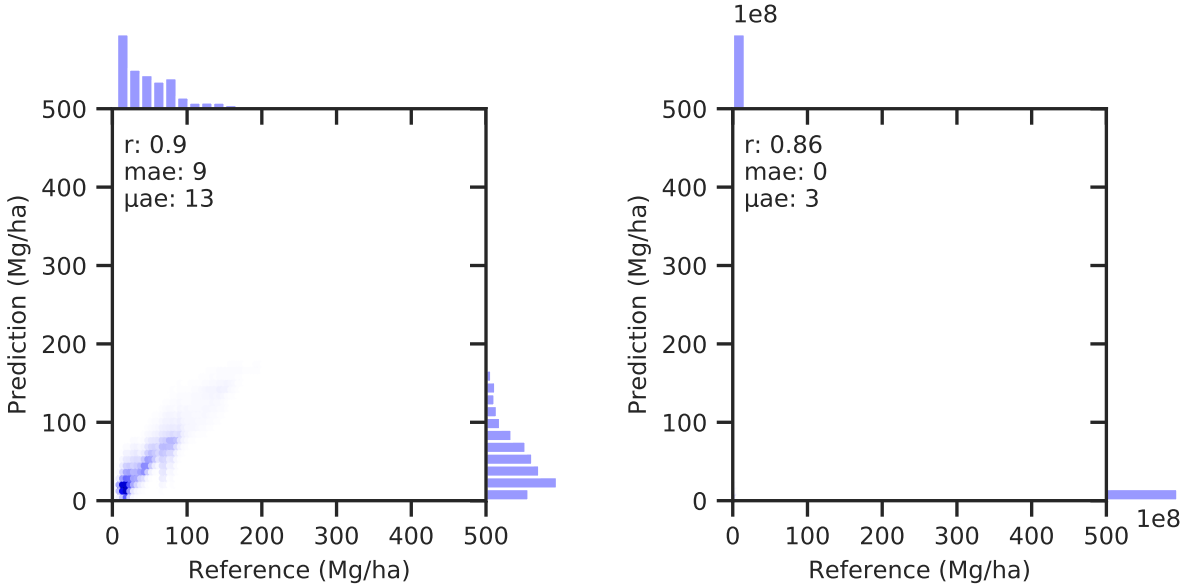
(b) Zero included

Cumulative density histogram (zone 25)

Return to zone table

Zone 26

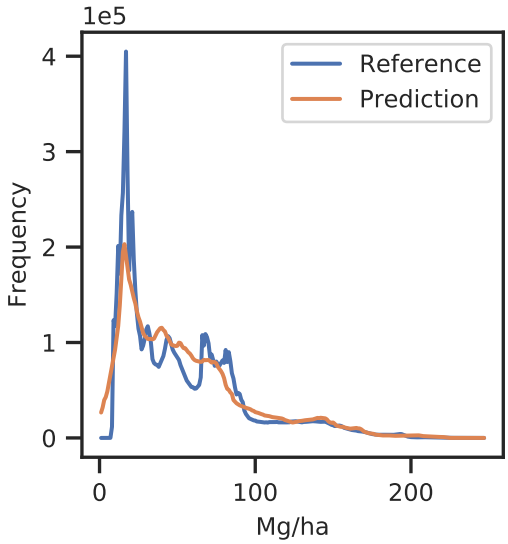
Zone map (zone 26)



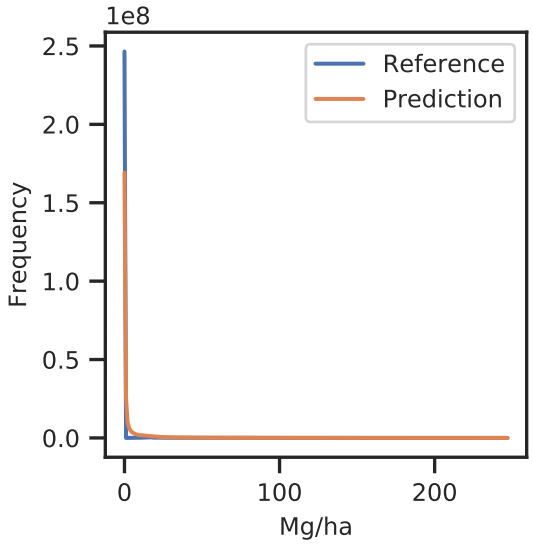
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 26)

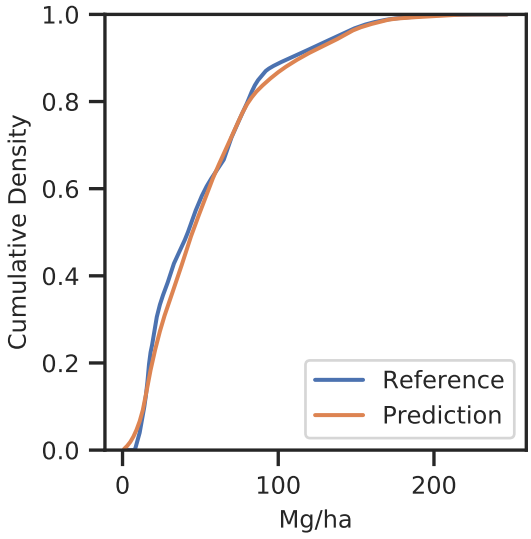


(a) Zero excluded

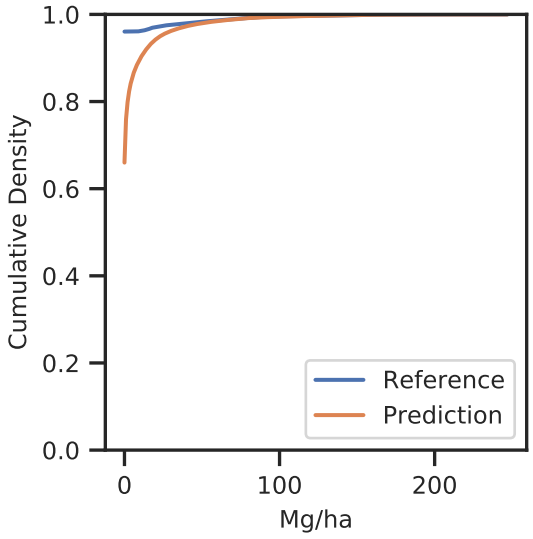


(b) Zero included

Ordinary frequency histogram (zone 26)



(a) Zero excluded



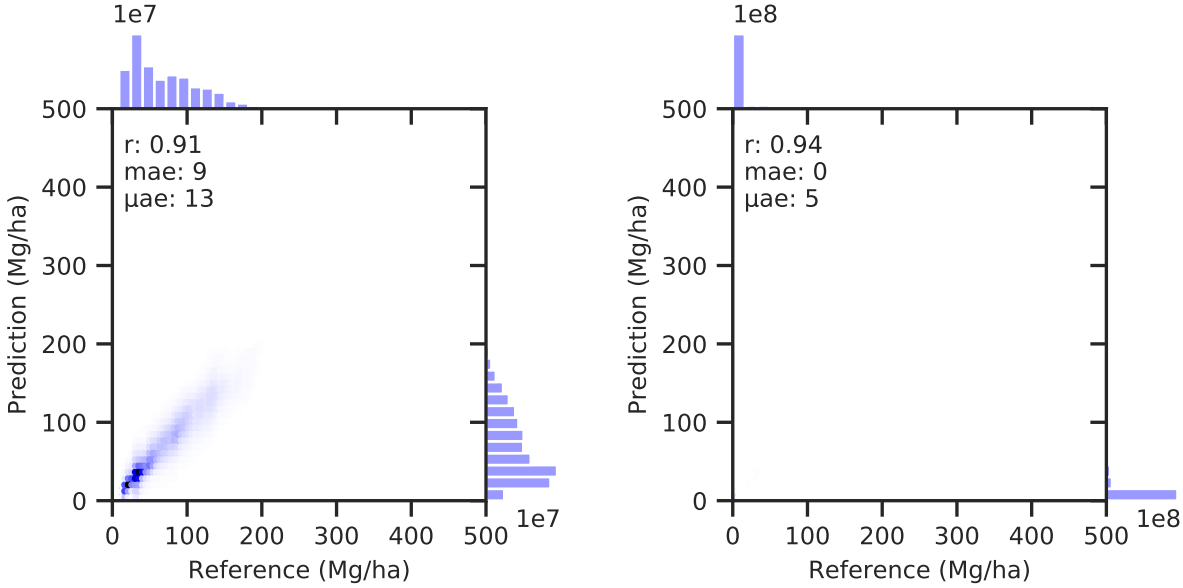
(b) Zero included

Cumulative density histogram (zone 26)

Return to zone table

Zone 27

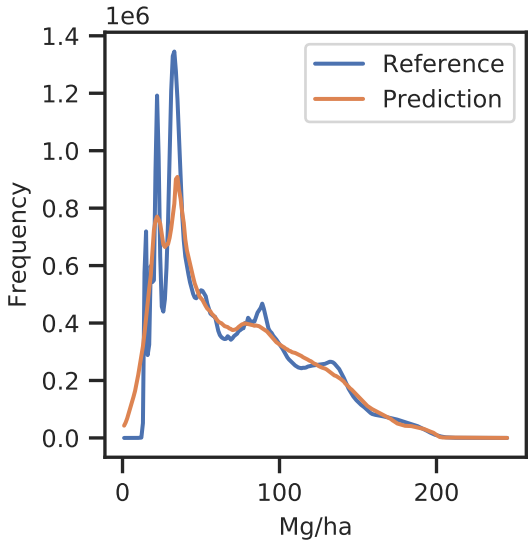
Zone map (zone 27)



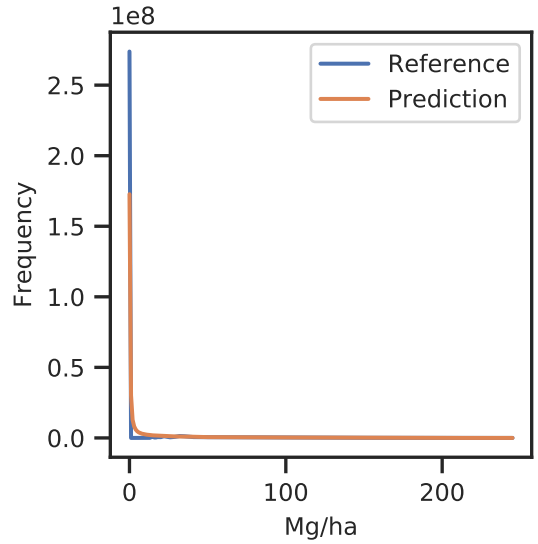
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 27)

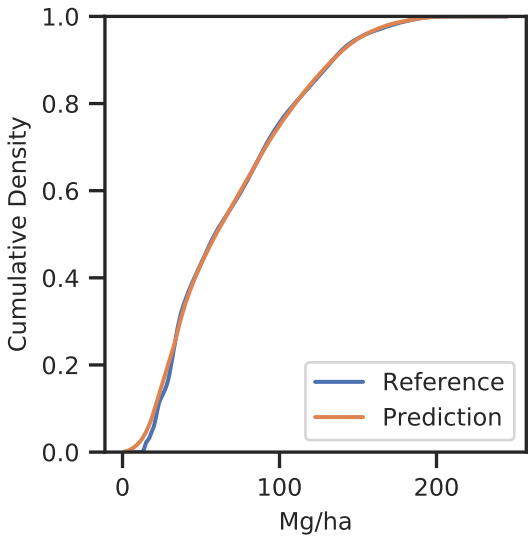


(a) Zero excluded

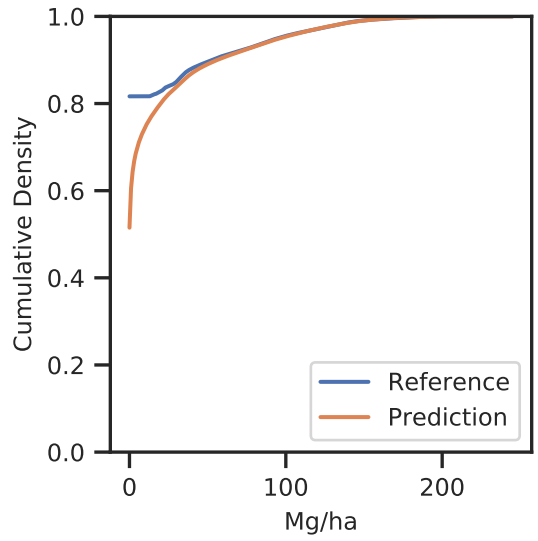


(b) Zero included

Ordinary frequency histogram (zone 27)



(a) Zero excluded



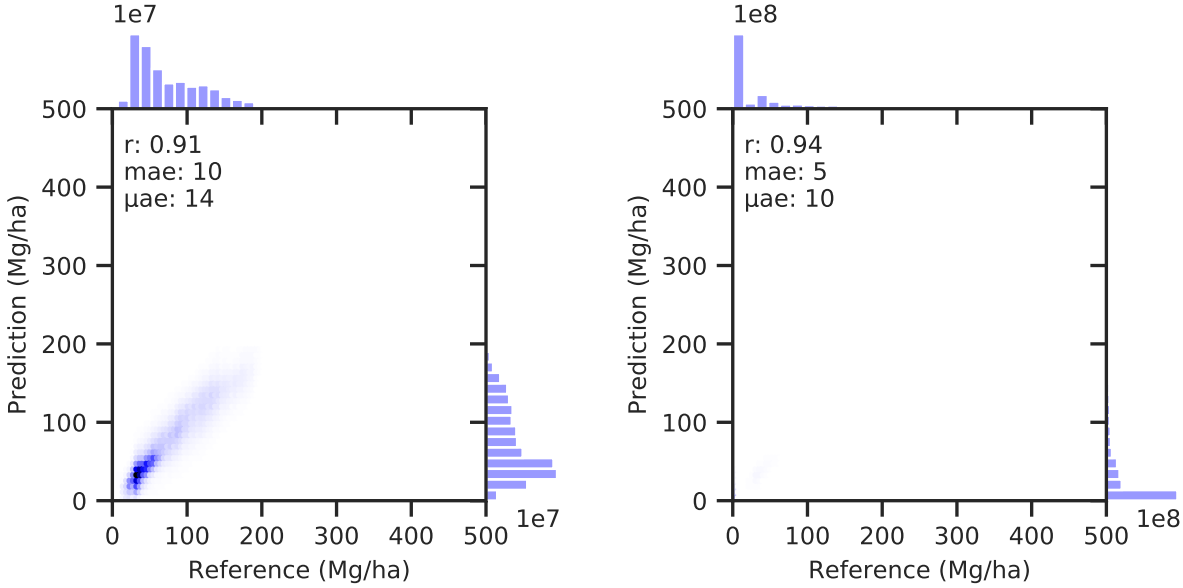
(b) Zero included

Cumulative density histogram (zone 27)

Return to zone table

Zone 28

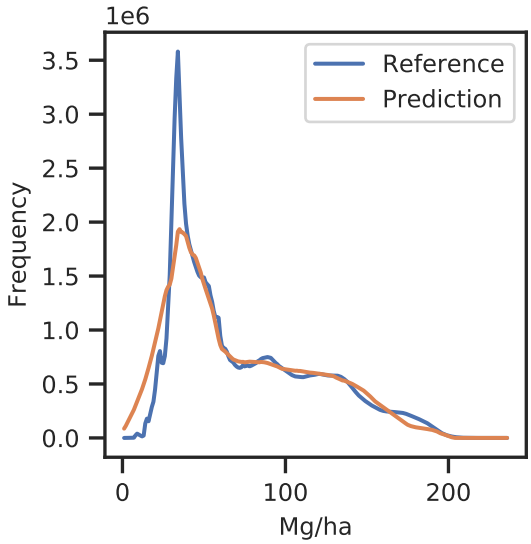
Zone map (zone 28)



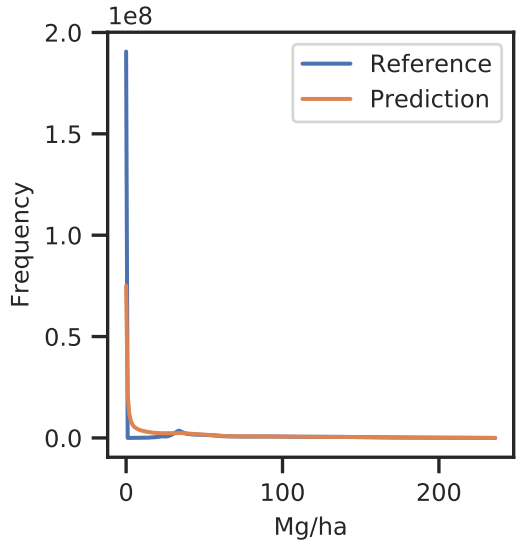
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 28)

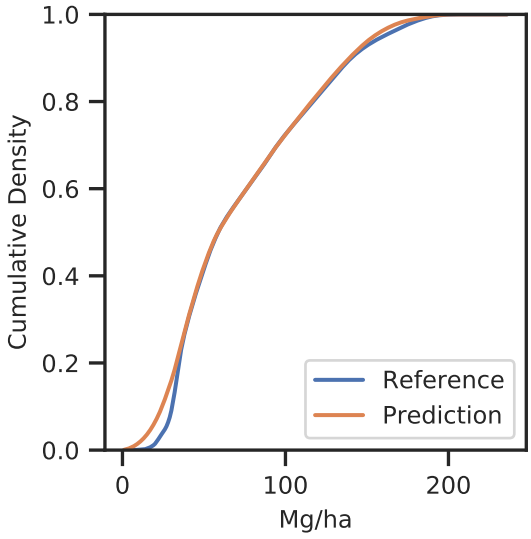


(a) Zero excluded

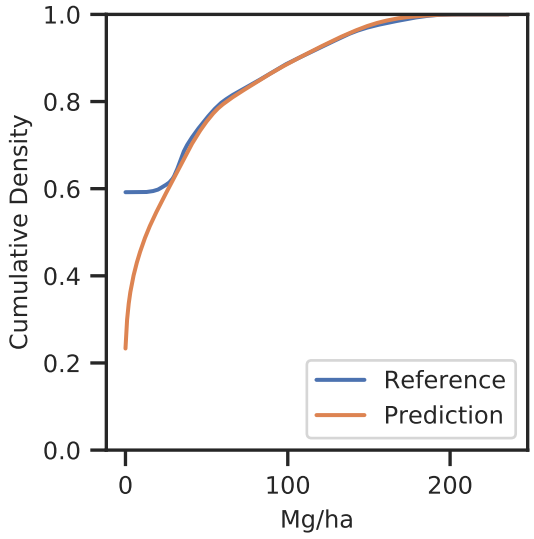


(b) Zero included

Ordinary frequency histogram (zone 28)



(a) Zero excluded



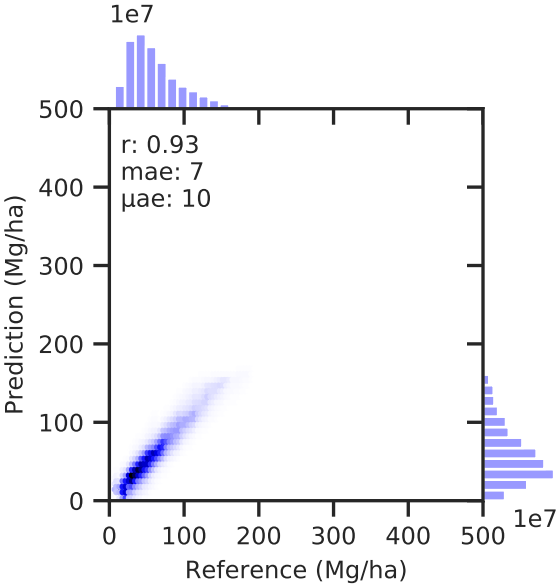
(b) Zero included

Cumulative density histogram (zone 28)

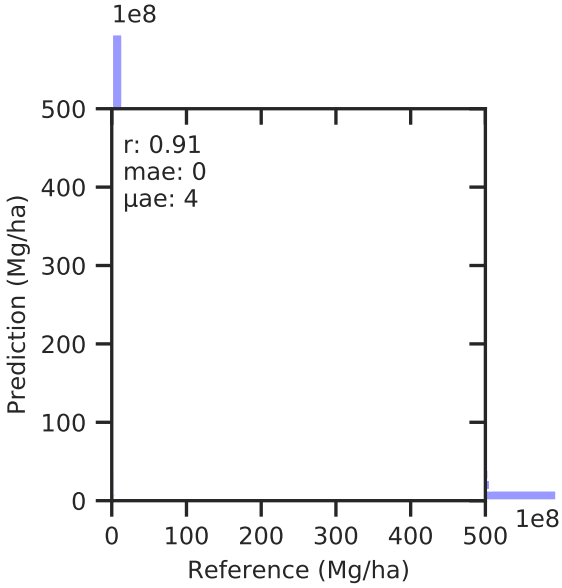
Return to zone table

Zone 29

Zone map (zone 29)

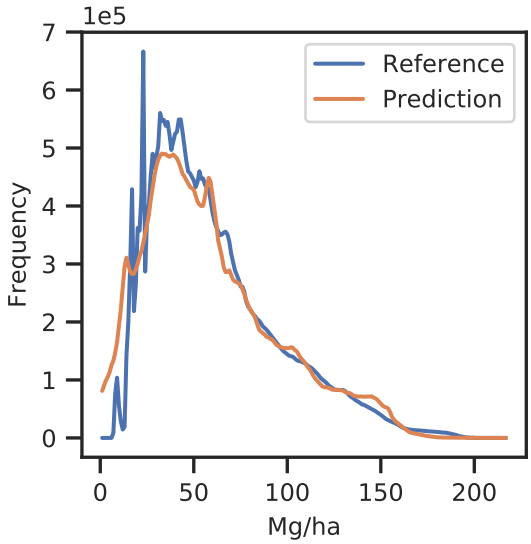


(a) Zero excluded

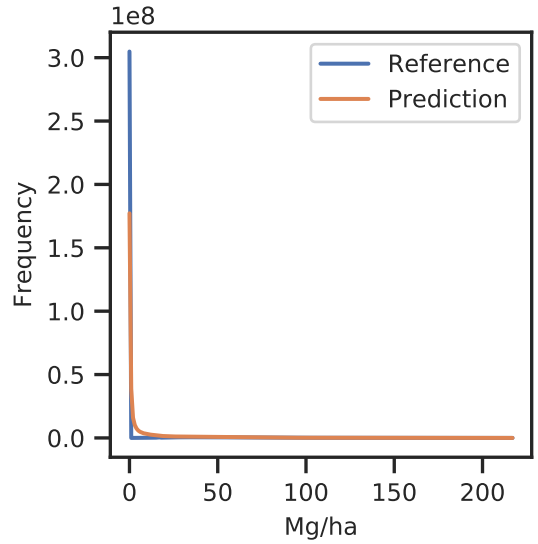


(b) Zero included

2-D frequency histogram (zone 29)

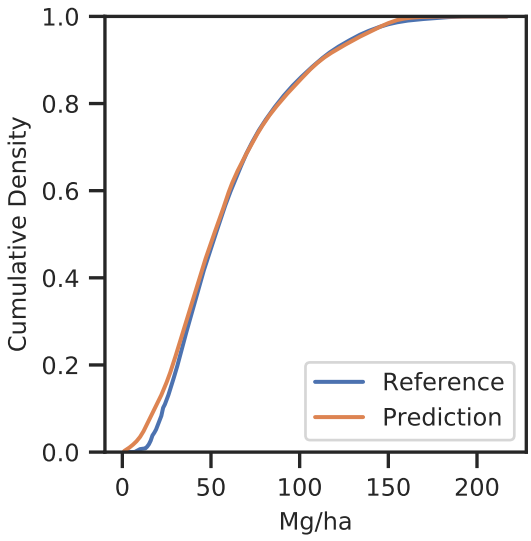


(a) Zero excluded

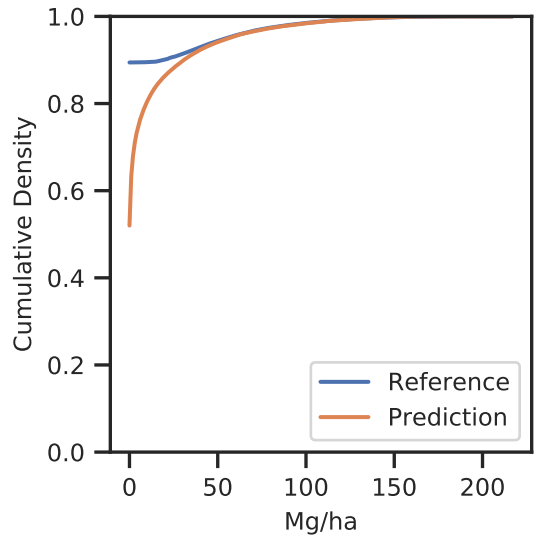


(b) Zero included

Ordinary frequency histogram (zone 29)



(a) Zero excluded



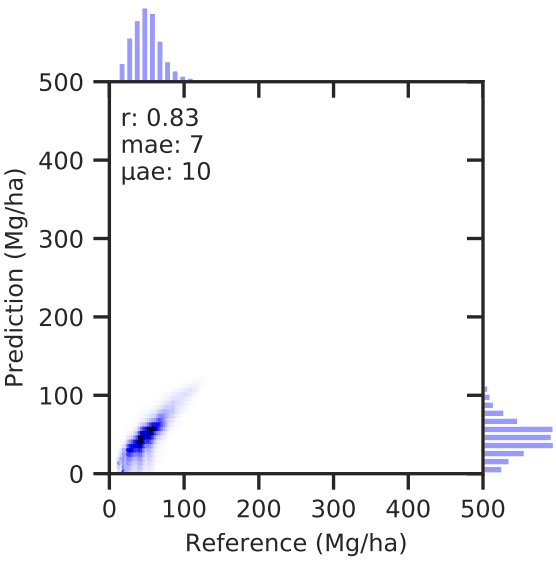
(b) Zero included

Cumulative density histogram (zone 29)

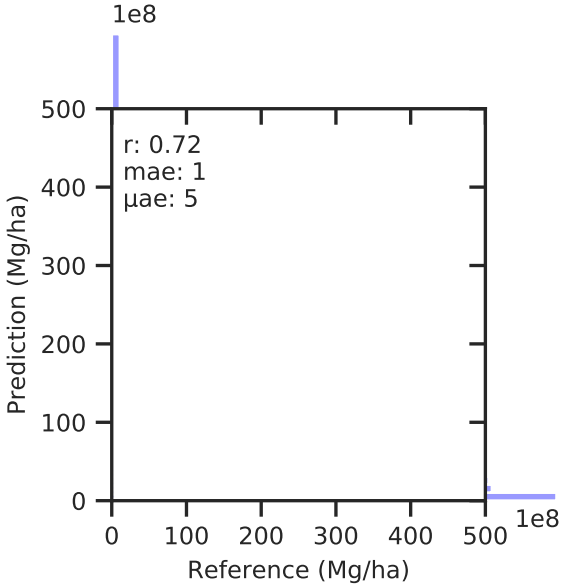
Return to zone table

Zone 30

Zone map (zone 30)

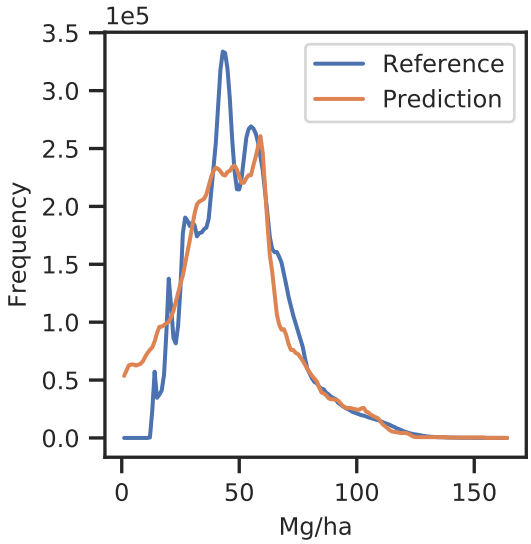


(a) Zero excluded

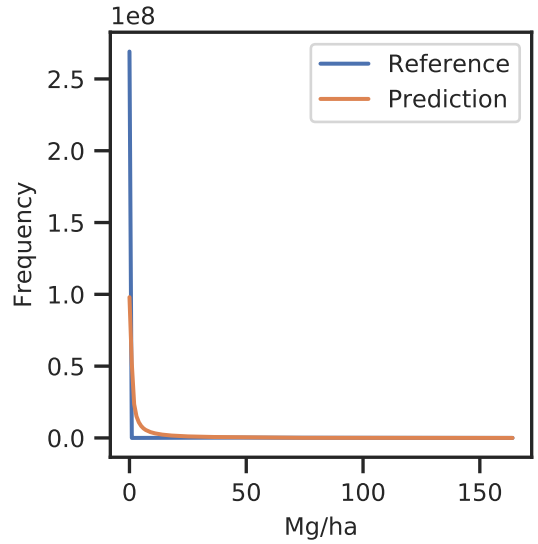


(b) Zero included

2-D frequency histogram (zone 30)

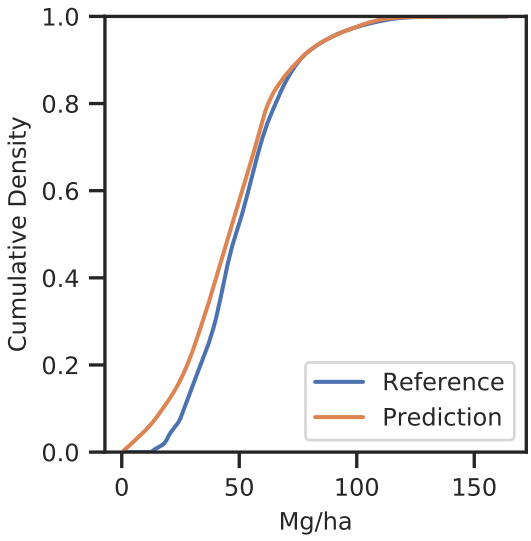


(a) Zero excluded

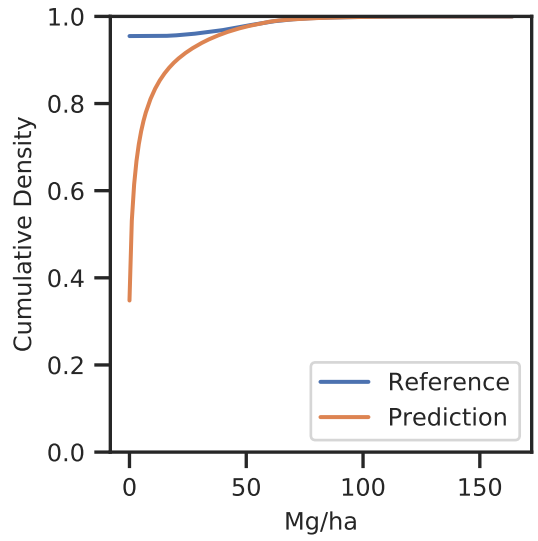


(b) Zero included

Ordinary frequency histogram (zone 30)



(a) Zero excluded



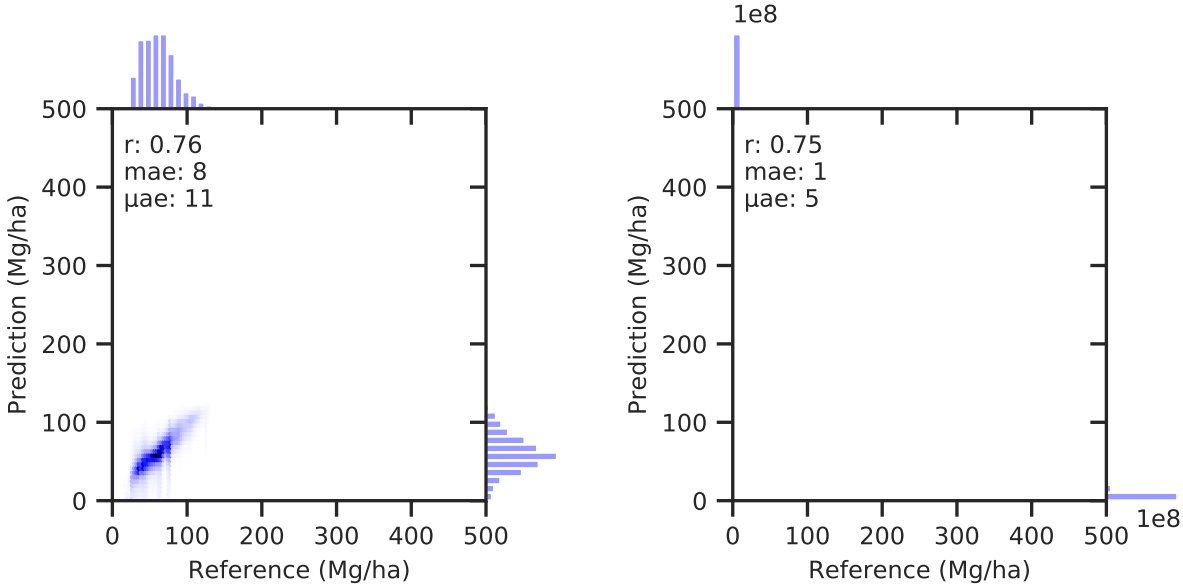
(b) Zero included

Cumulative density histogram (zone 30)

Return to zone table

Zone 31

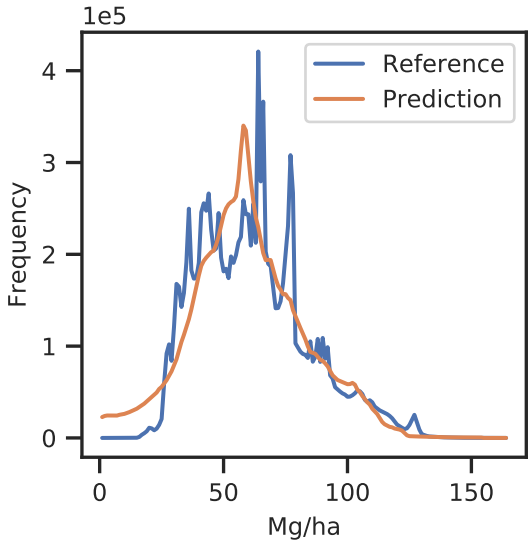
Zone map (zone 31)



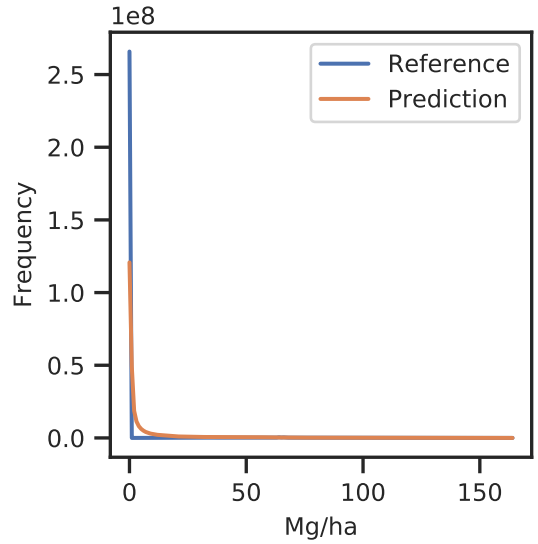
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 31)

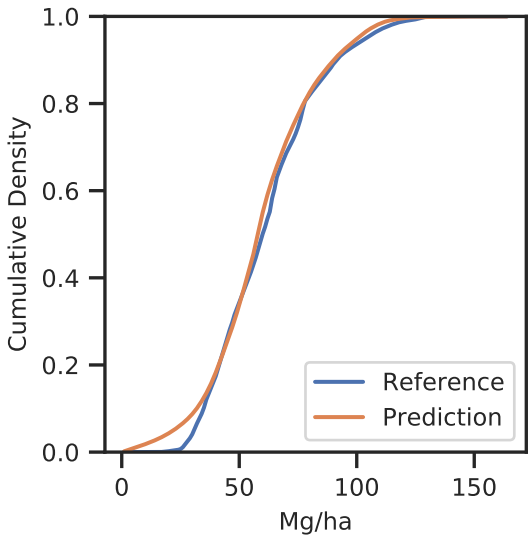


(a) Zero excluded

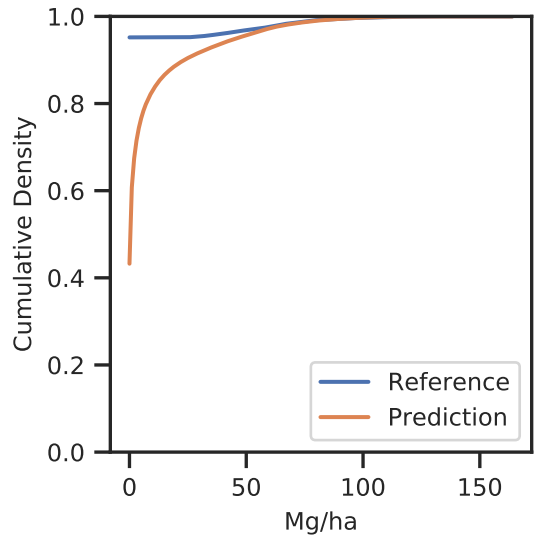


(b) Zero included

Ordinary frequency histogram (zone 31)



(a) Zero excluded



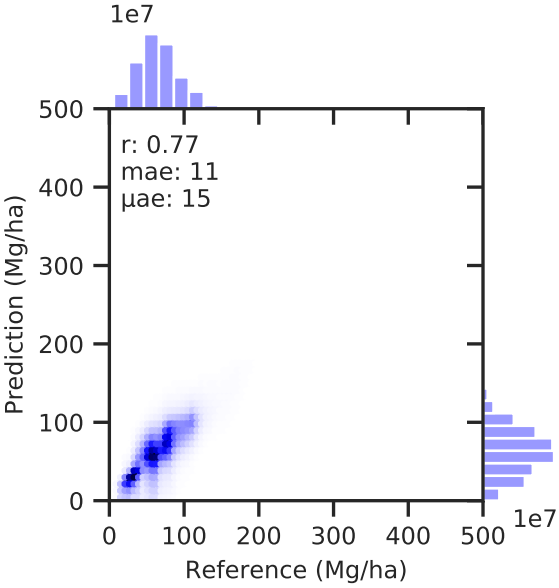
(b) Zero included

Cumulative density histogram (zone 31)

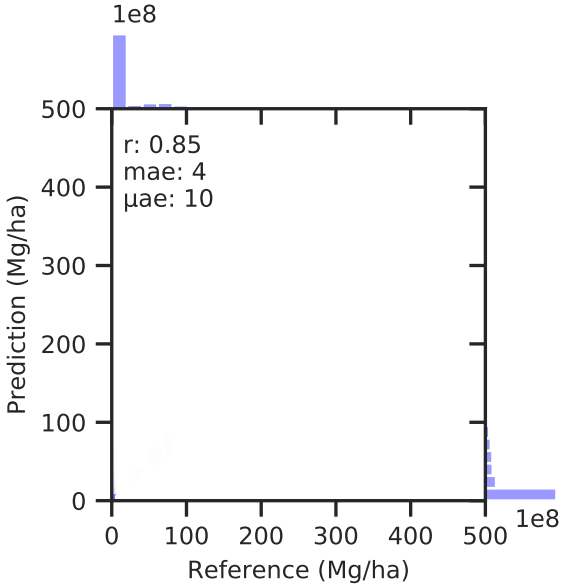
Return to zone table

Zone 32

Zone map (zone 32)

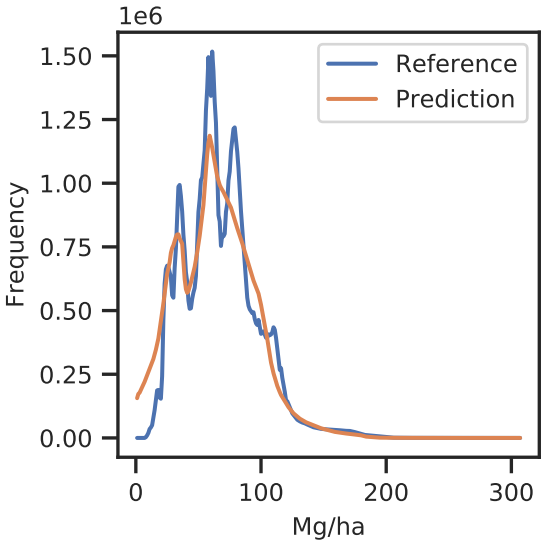


(a) Zero excluded

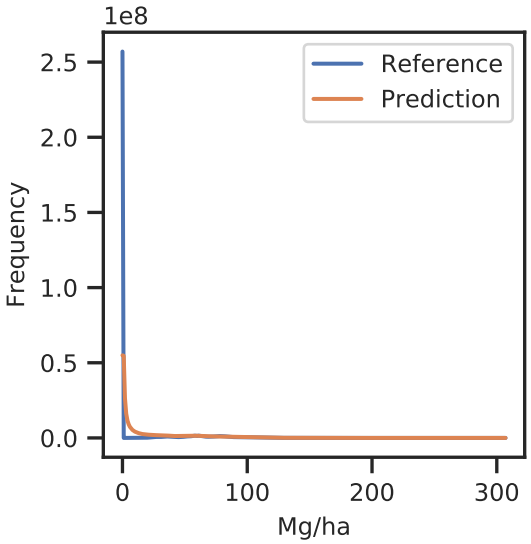


(b) Zero included

2-D frequency histogram (zone 32)

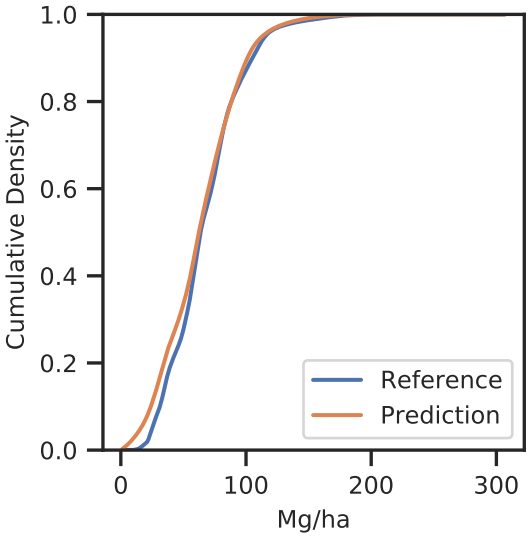


(a) Zero excluded

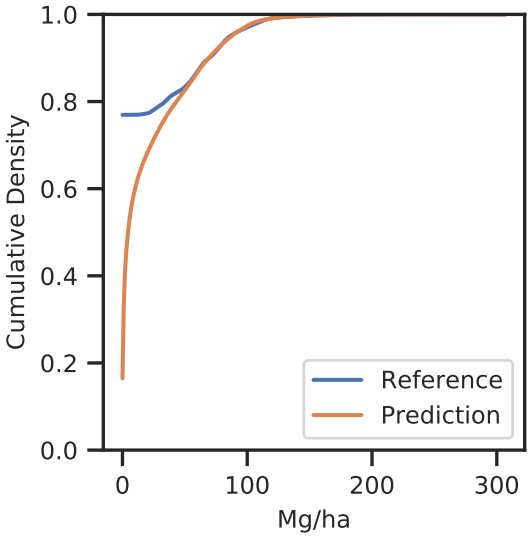


(b) Zero included

Ordinary frequency histogram (zone 32)



(a) Zero excluded



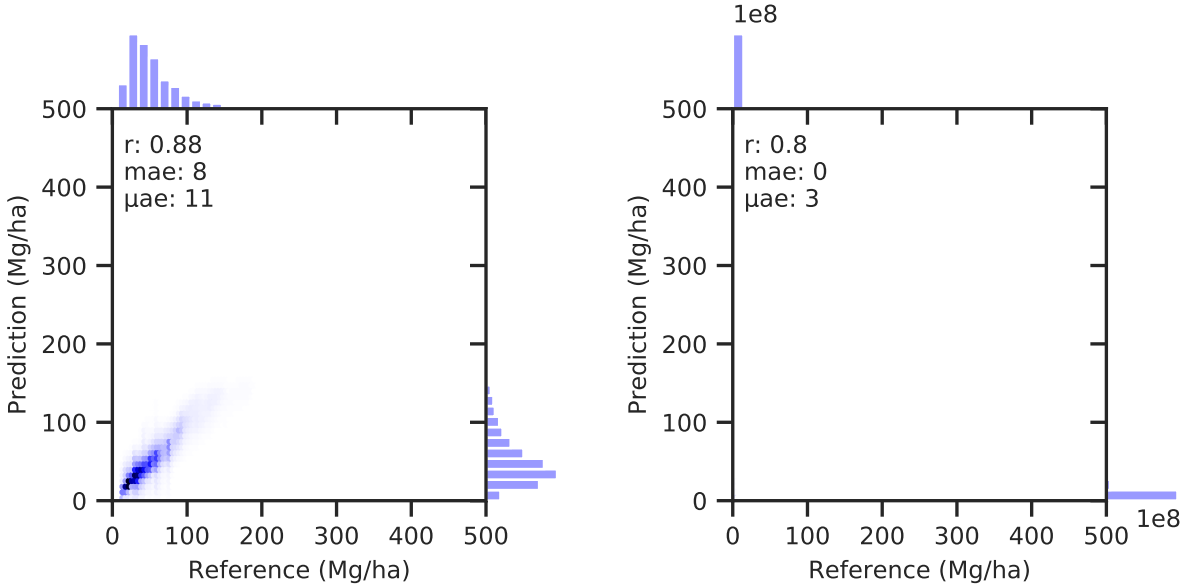
(b) Zero included

Cumulative density histogram (zone 32)

Return to zone table

Zone 33

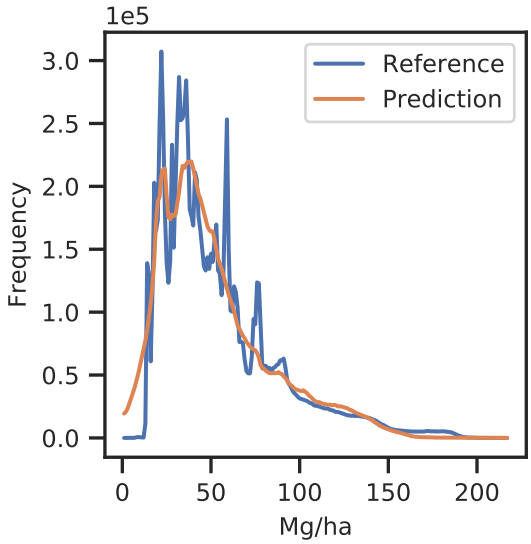
Zone map (zone 33)



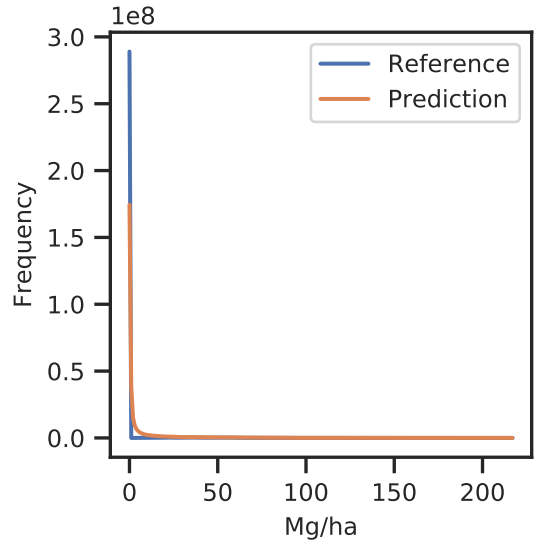
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 33)

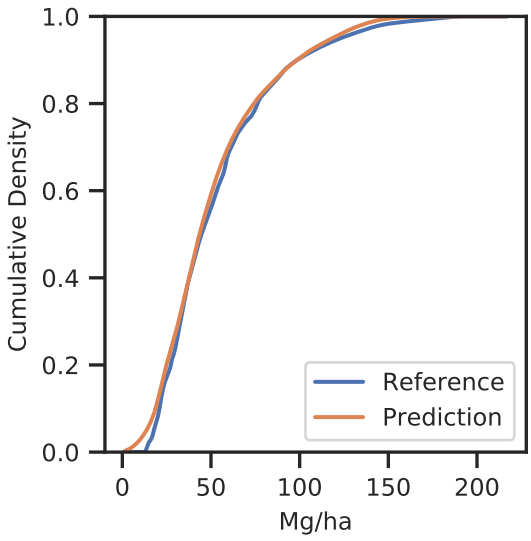


(a) Zero excluded

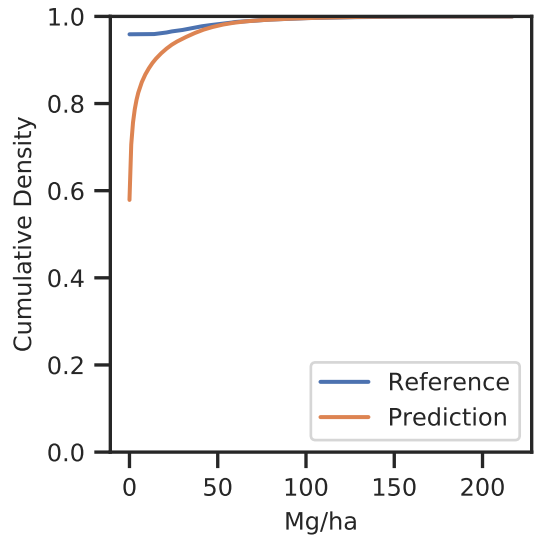


(b) Zero included

Ordinary frequency histogram (zone 33)



(a) Zero excluded

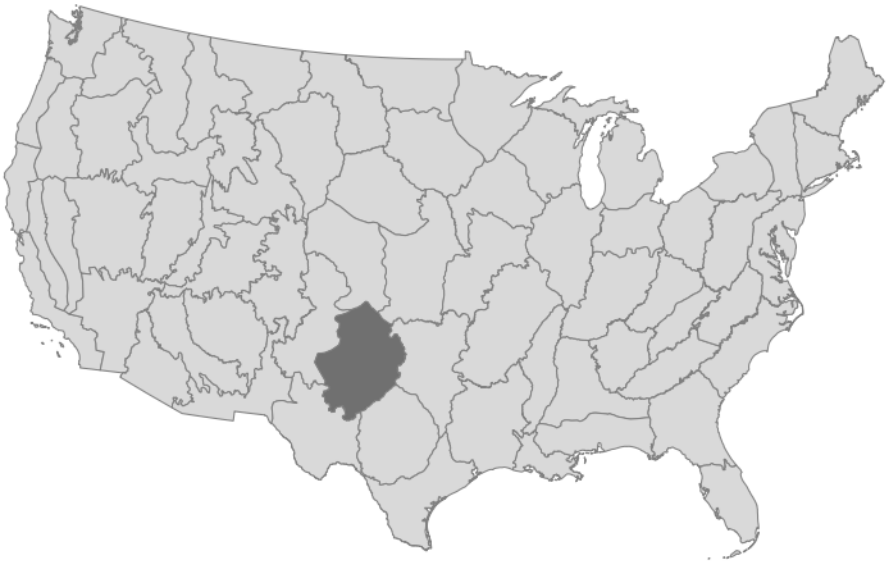


(b) Zero included

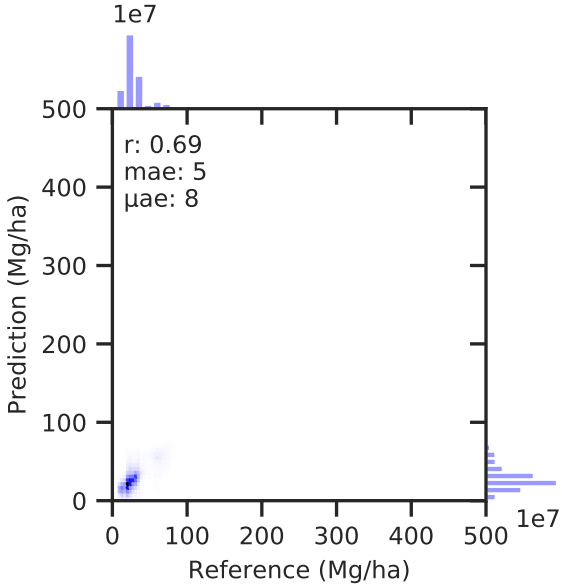
Cumulative density histogram (zone 33)

Return to zone table

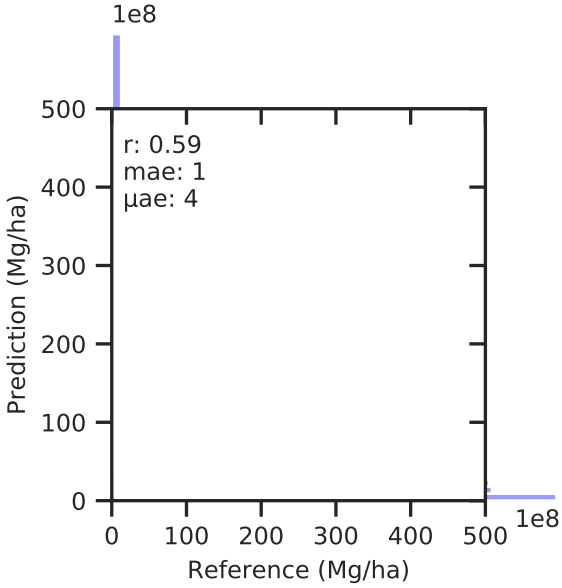
Zone 34



Zone map (zone 34)

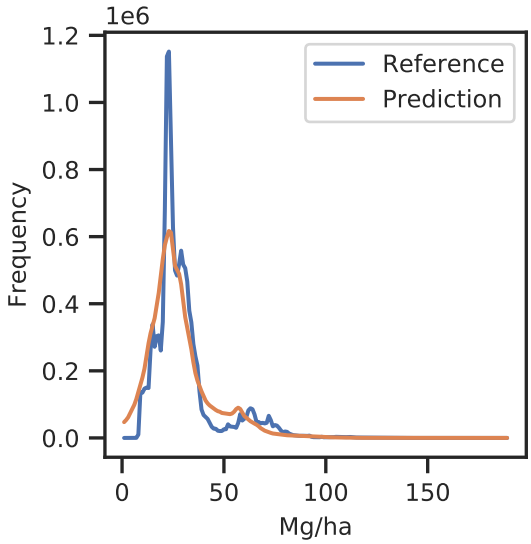


(a) Zero excluded

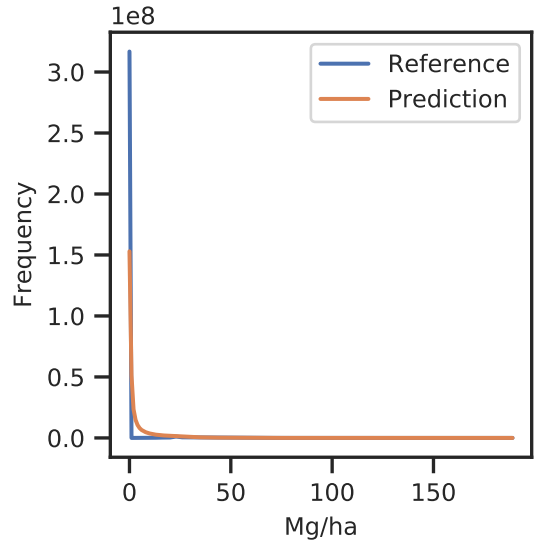


(b) Zero included

2-D frequency histogram (zone 34)

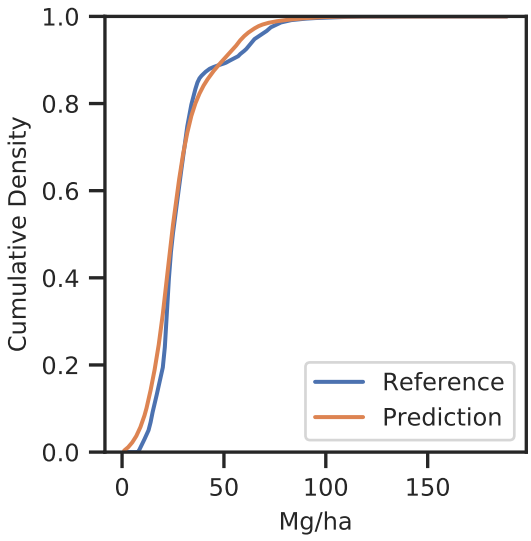


(a) Zero excluded

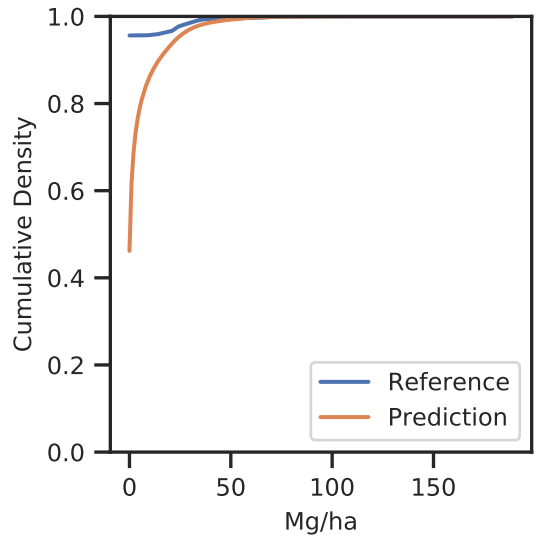


(b) Zero included

Ordinary frequency histogram (zone 34)



(a) Zero excluded



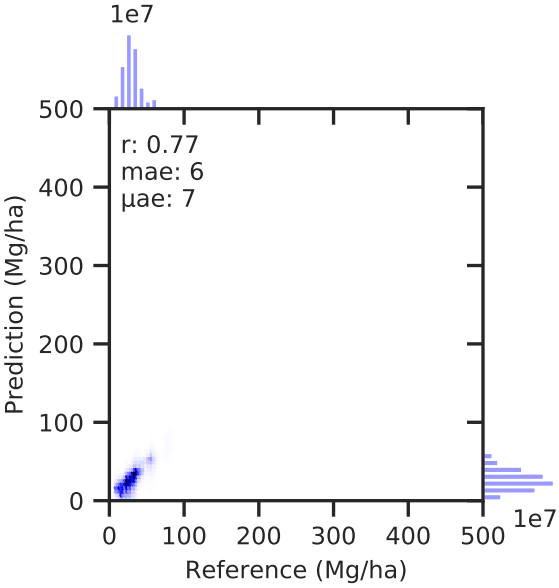
(b) Zero included

Cumulative density histogram (zone 34)

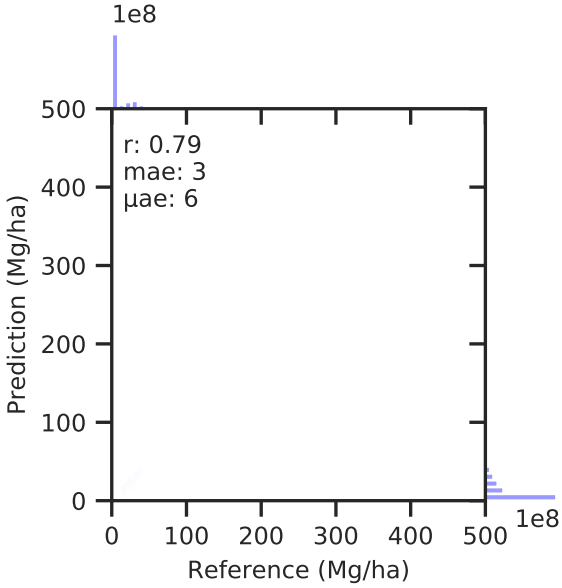
Return to zone table

Zone 35

Zone map (zone 35)

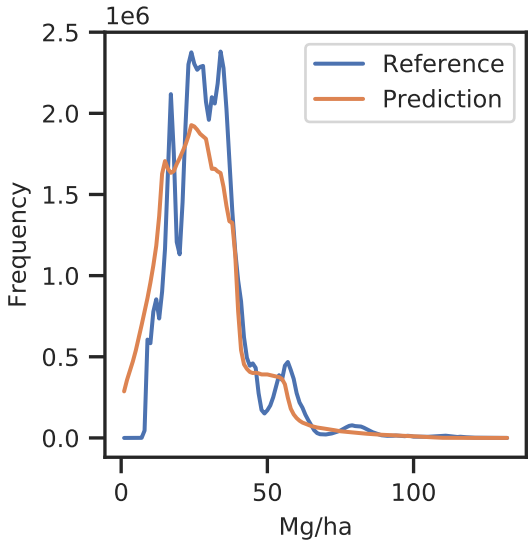


(a) Zero excluded

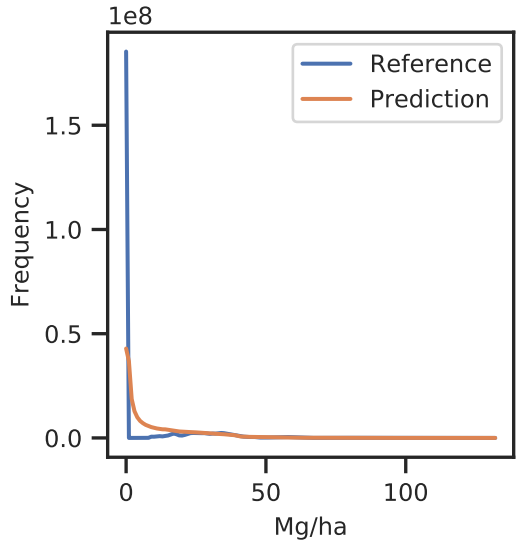


(b) Zero included

2-D frequency histogram (zone 35)

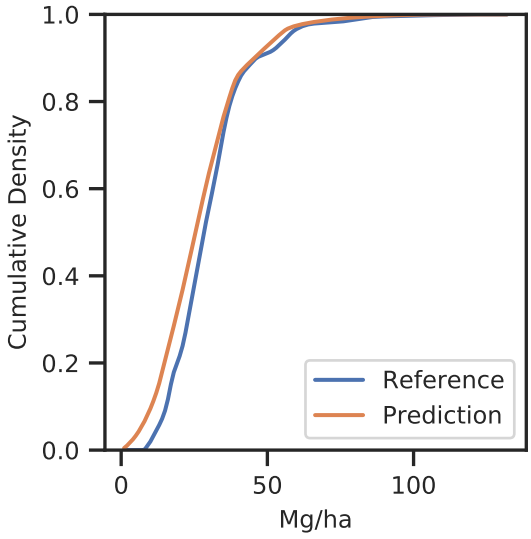


(a) Zero excluded

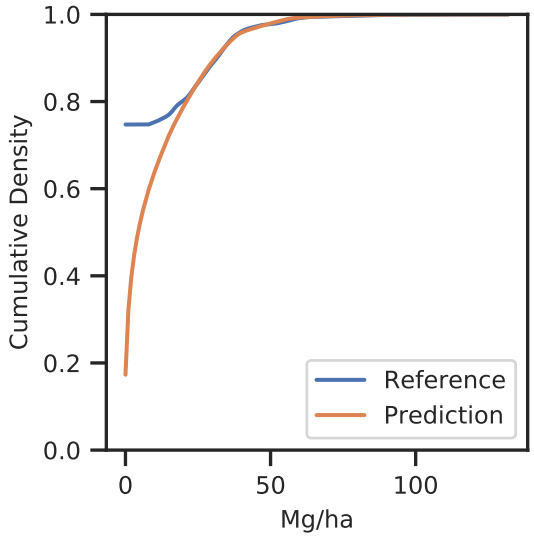


(b) Zero included

Ordinary frequency histogram (zone 35)



(a) Zero excluded



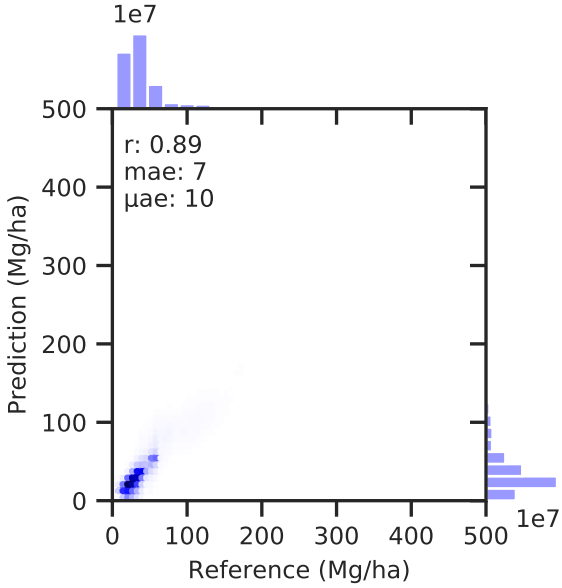
(b) Zero included

Cumulative density histogram (zone 35)

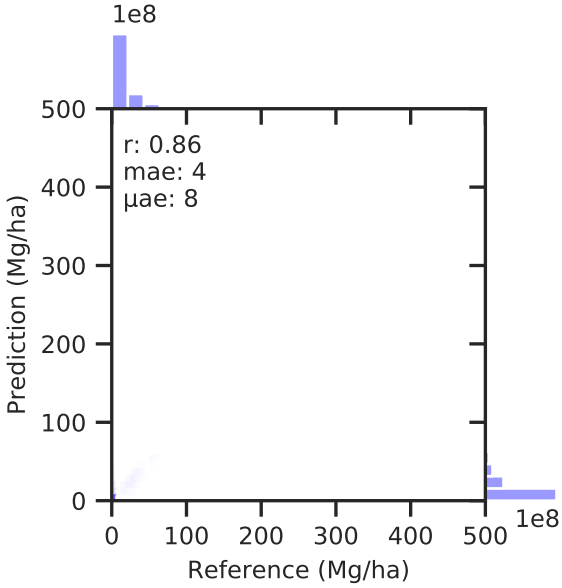
Return to zone table

Zone 36

Zone map (zone 36)

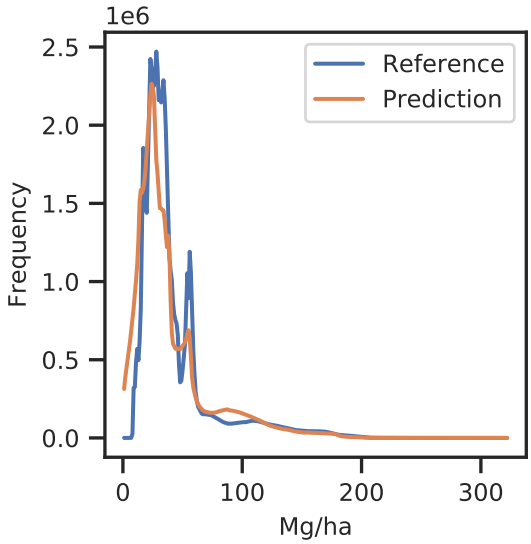


(a) Zero excluded

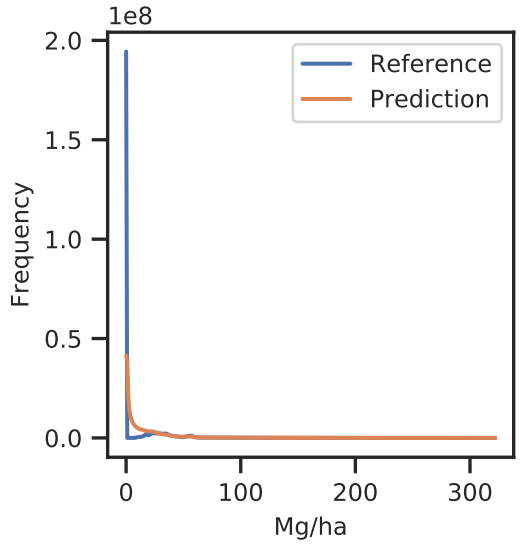


(b) Zero included

2-D frequency histogram (zone 36)

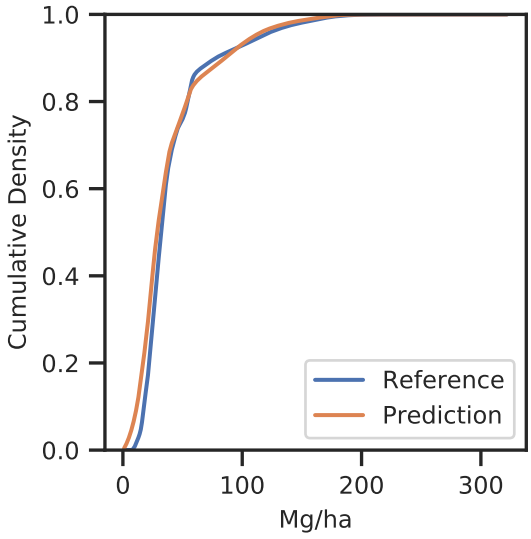


(a) Zero excluded

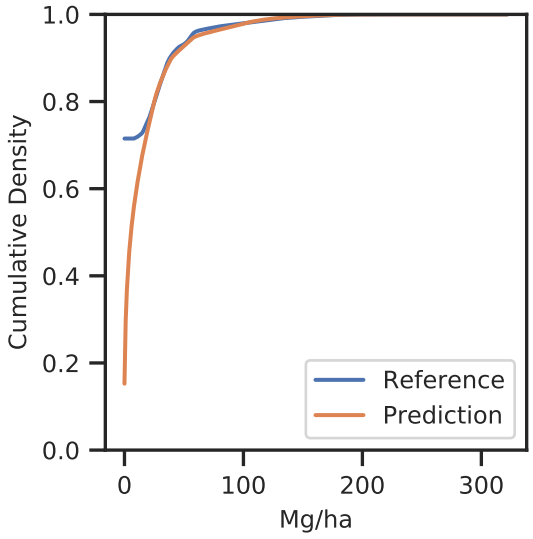


(b) Zero included

Ordinary frequency histogram (zone 36)



(a) Zero excluded



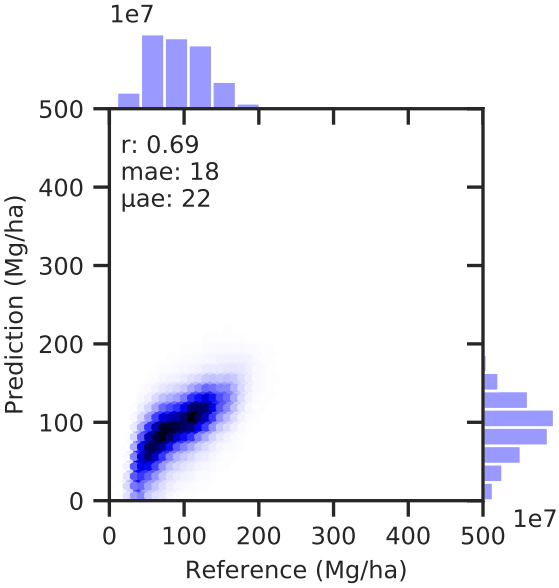
(b) Zero included

Cumulative density histogram (zone 36)

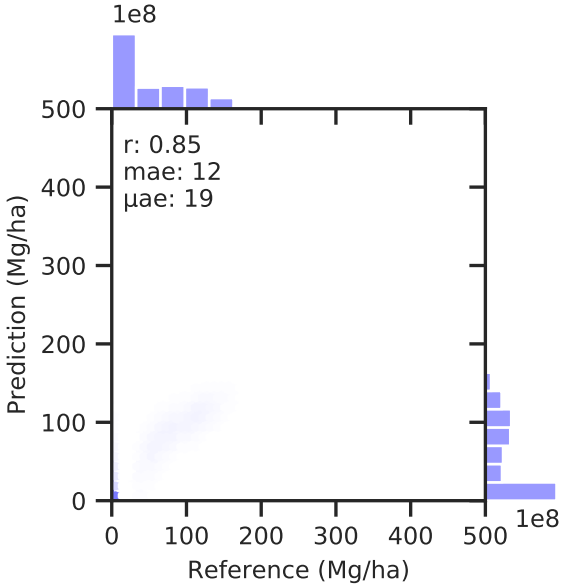
Return to zone table

Zone 37

Zone map (zone 37)

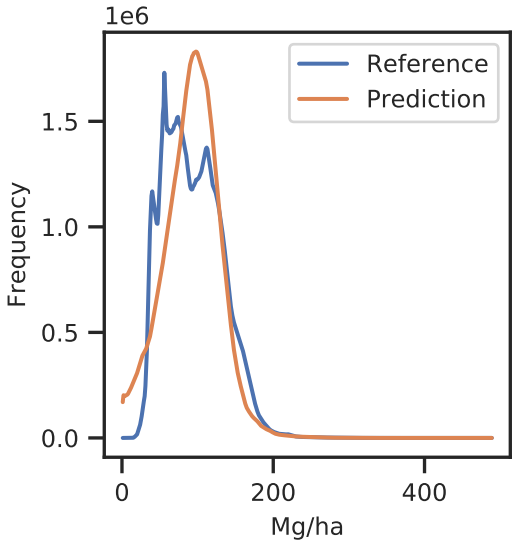


(a) Zero excluded

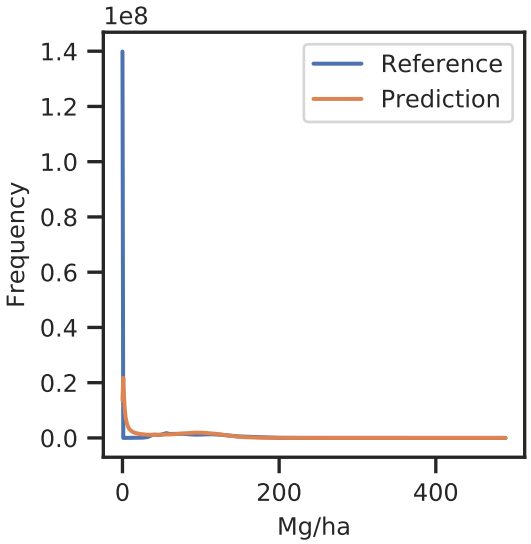


(b) Zero included

2-D frequency histogram (zone 37)

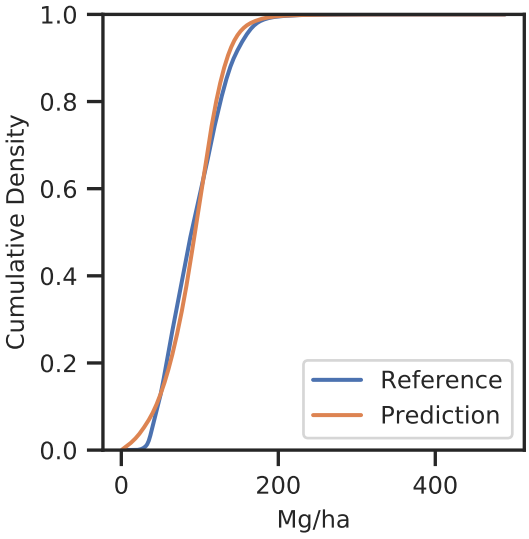


(a) Zero excluded

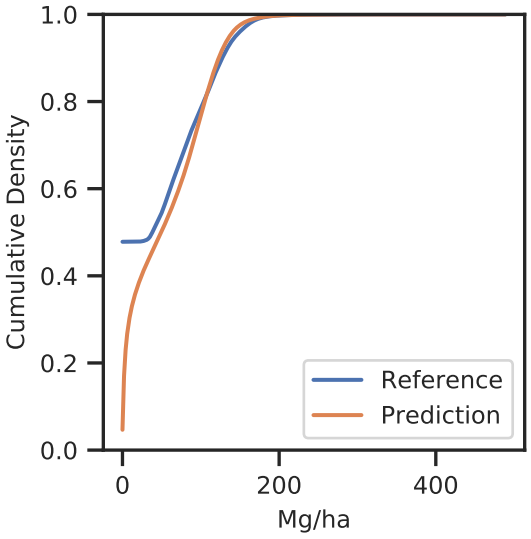


(b) Zero included

Ordinary frequency histogram (zone 37)



(a) Zero excluded



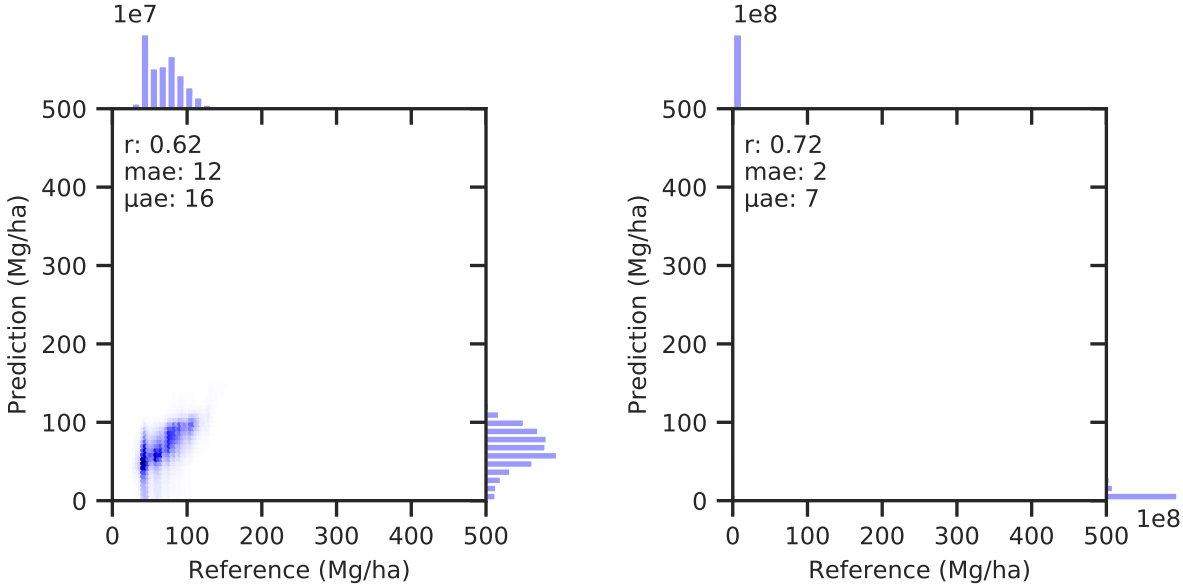
(b) Zero included

Cumulative density histogram (zone 37)

Return to zone table

Zone 38

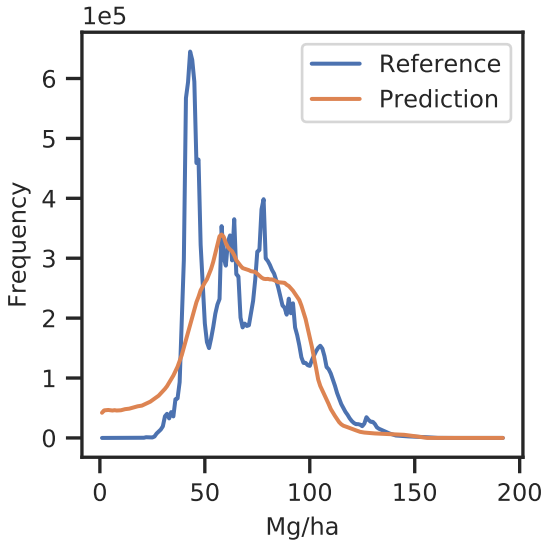
Zone map (zone 38)



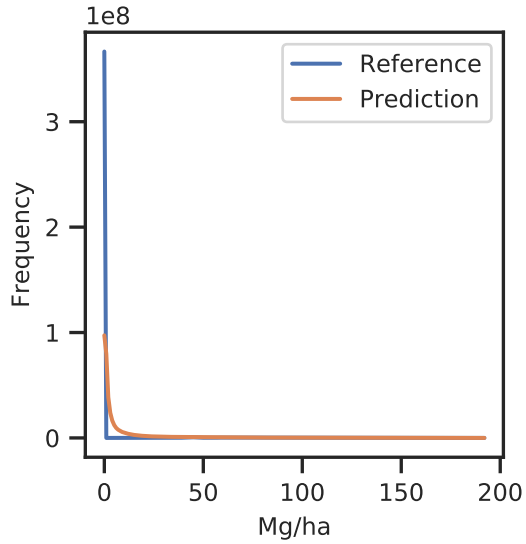
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 38)

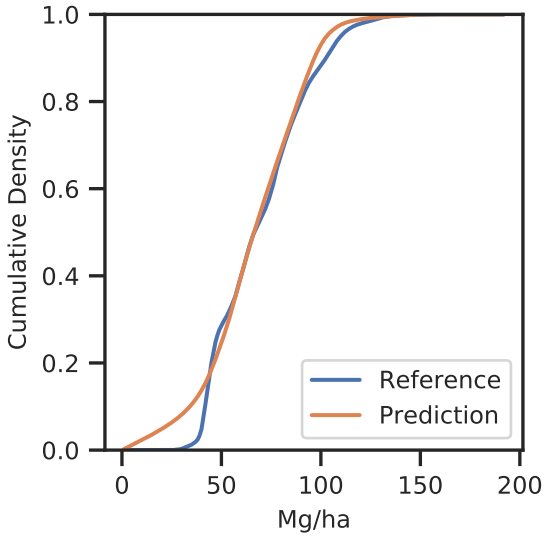


(a) Zero excluded

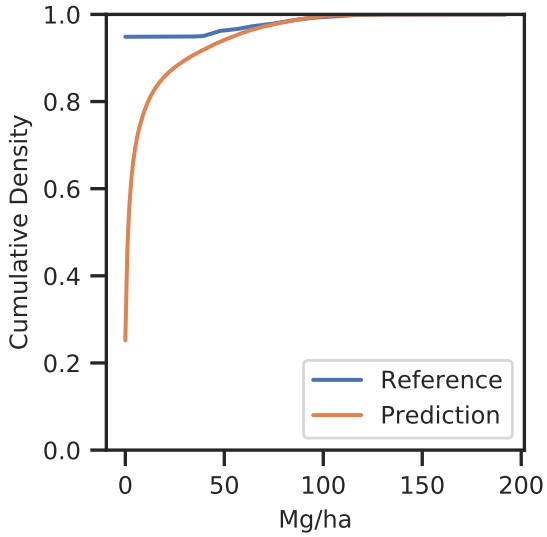


(b) Zero included

Ordinary frequency histogram (zone 38)



(a) Zero excluded



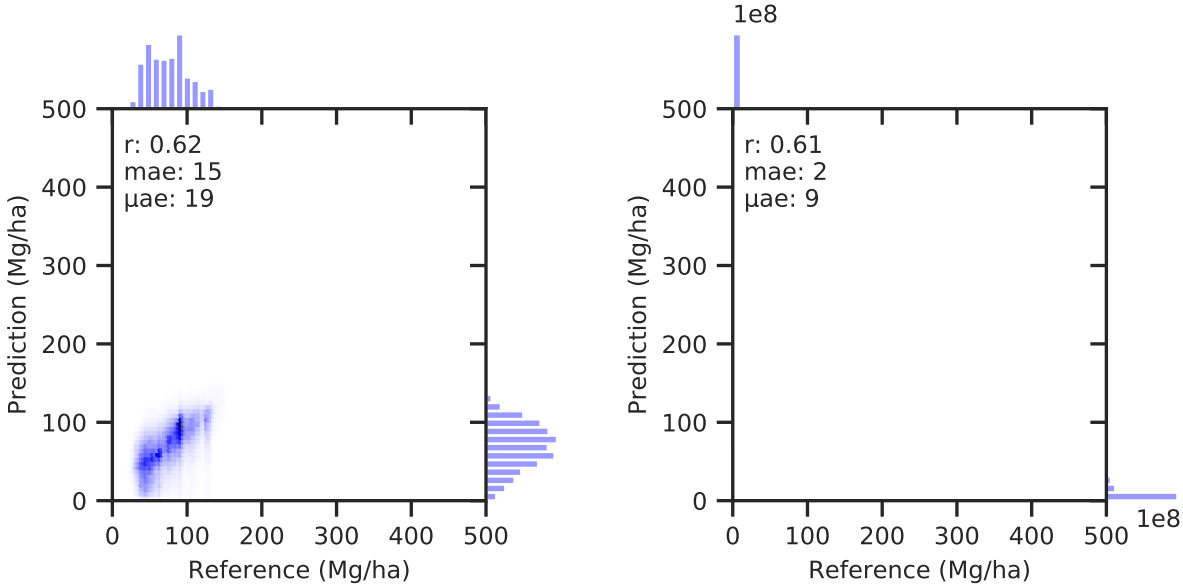
(b) Zero included

Cumulative density histogram (zone 38)

Return to zone table

Zone 39

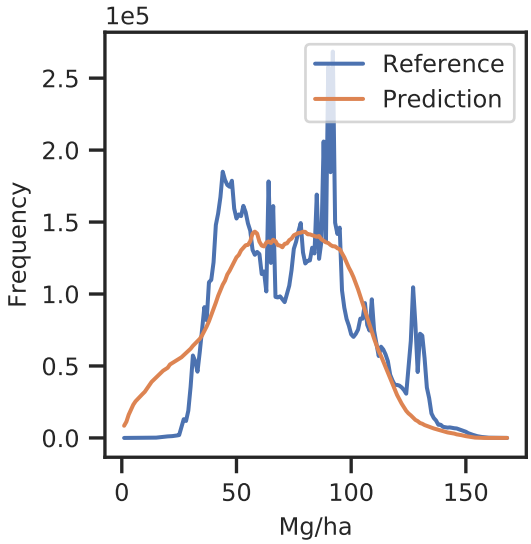
Zone map (zone 39)



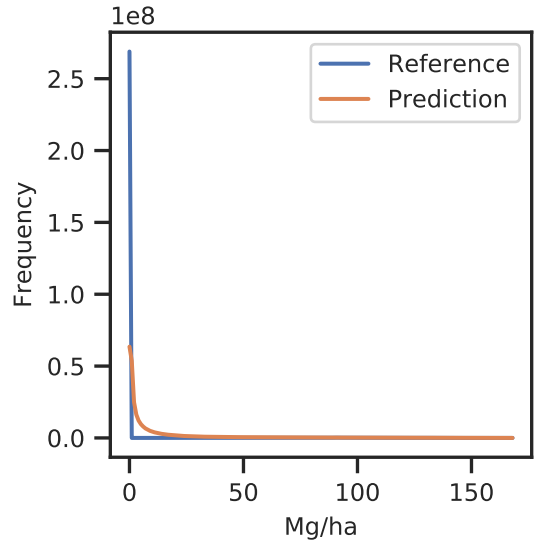
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 39)

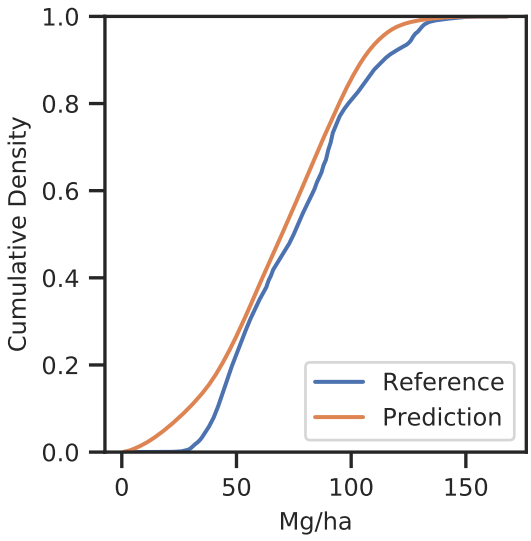


(a) Zero excluded

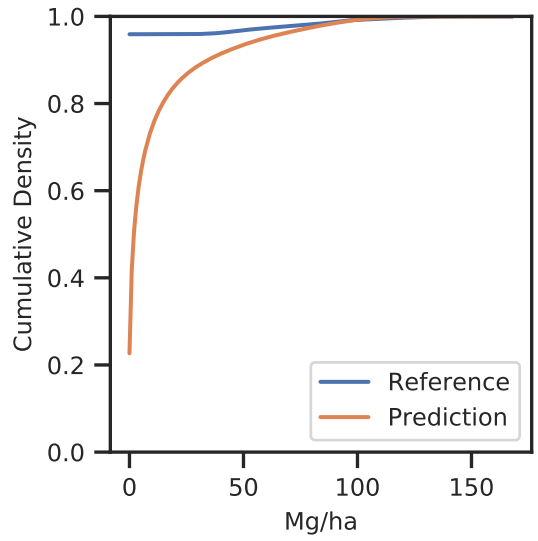


(b) Zero included

Ordinary frequency histogram (zone 39)



(a) Zero excluded



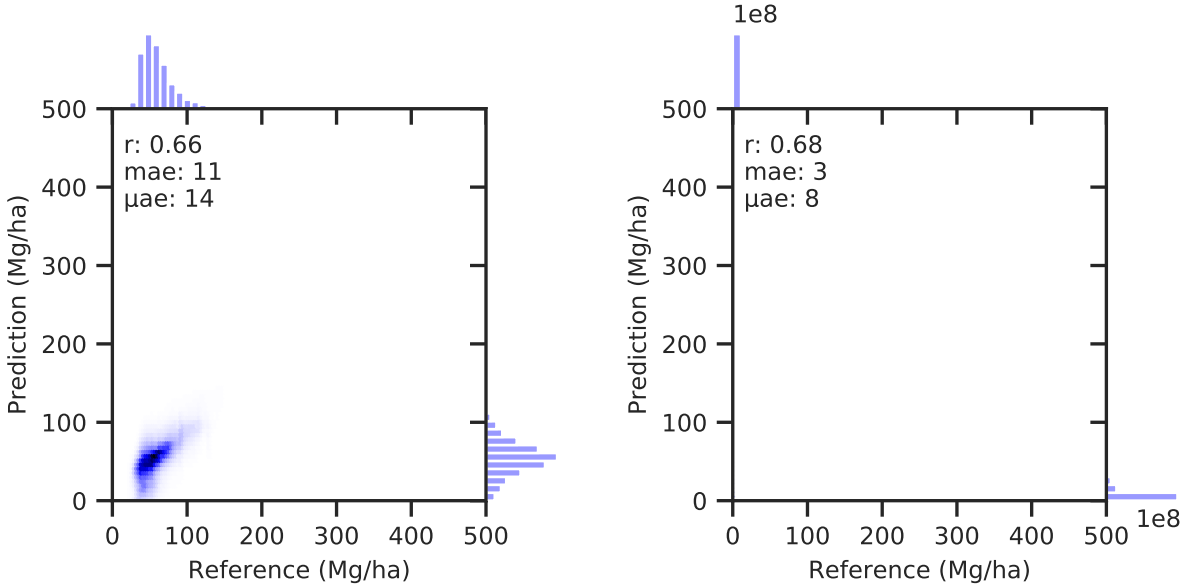
(b) Zero included

Cumulative density histogram (zone 39)

Return to zone table

Zone 40

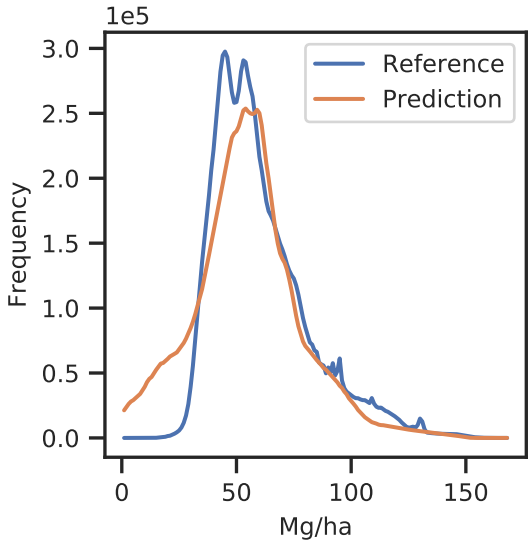
Zone map (zone 40)



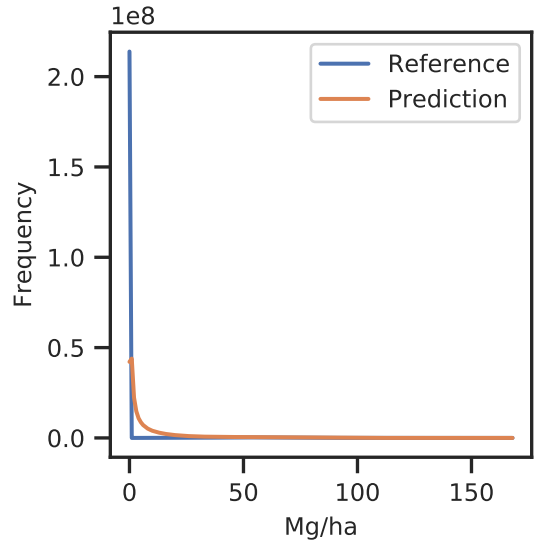
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 40)

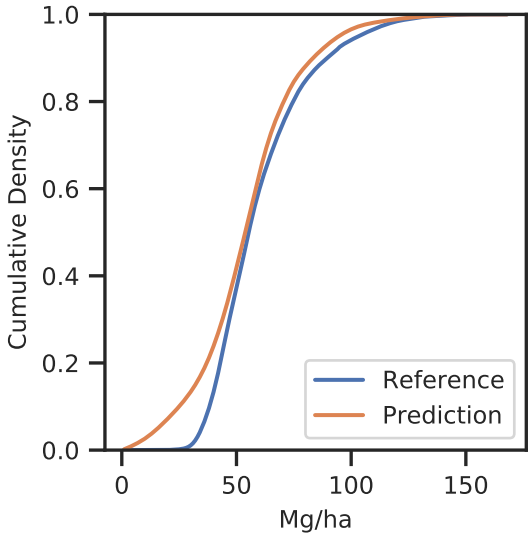


(a) Zero excluded

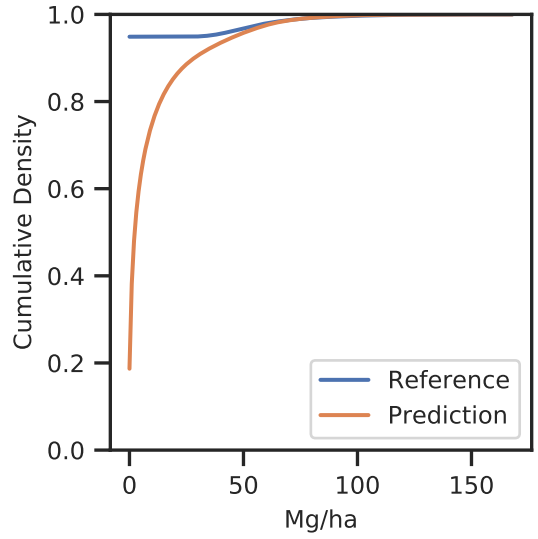


(b) Zero included

Ordinary frequency histogram (zone 40)



(a) Zero excluded



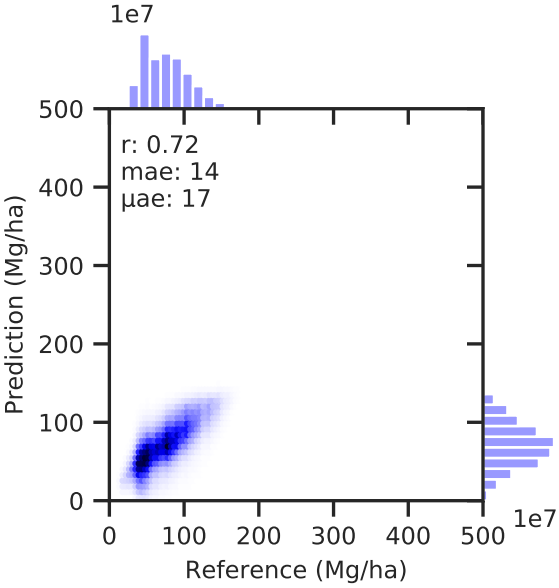
(b) Zero included

Cumulative density histogram (zone 40)

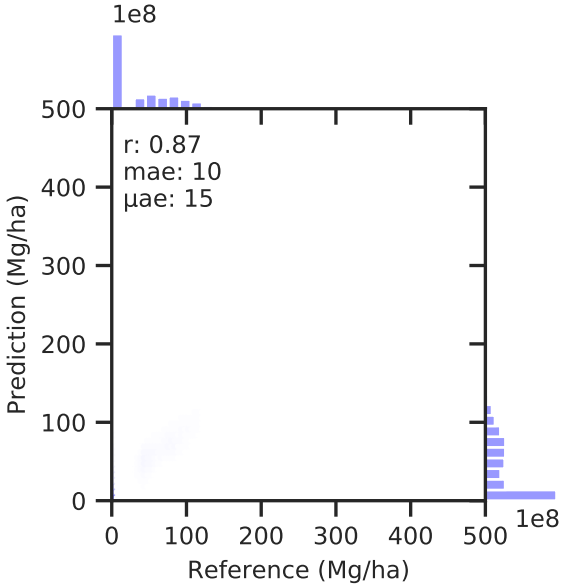
Return to zone table

Zone 41

Zone map (zone 41)

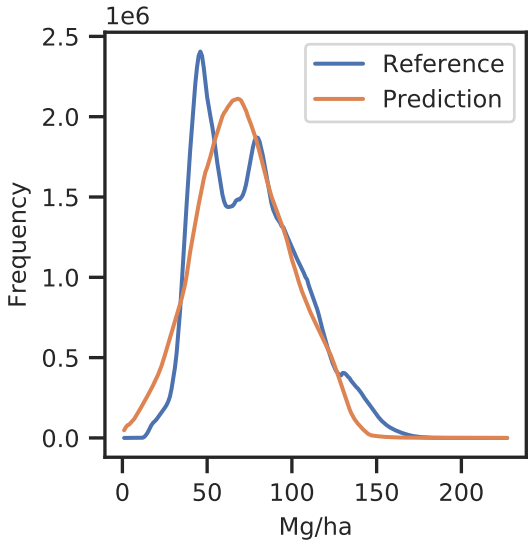


(a) Zero excluded

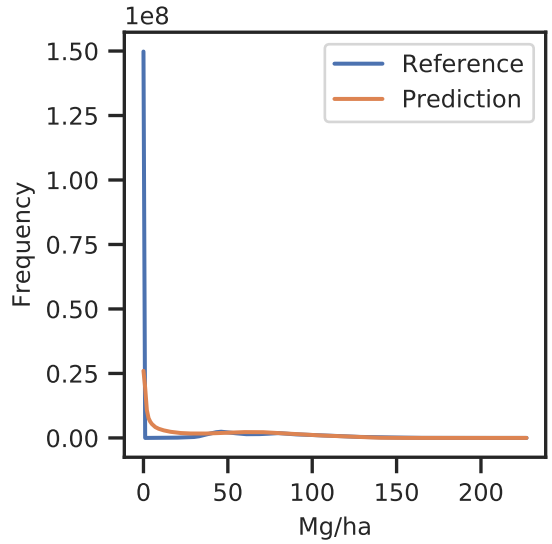


(b) Zero included

2-D frequency histogram (zone 41)

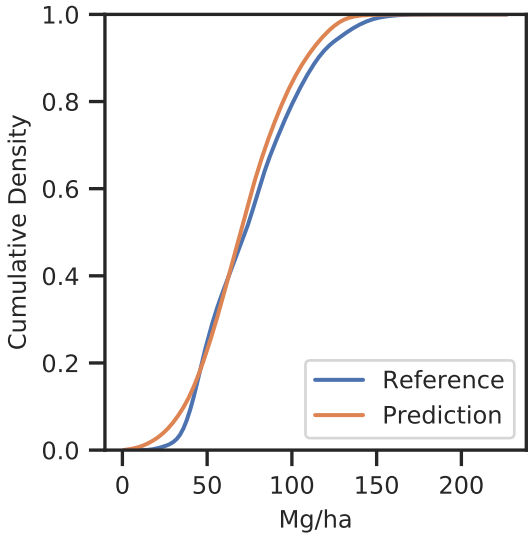


(a) Zero excluded

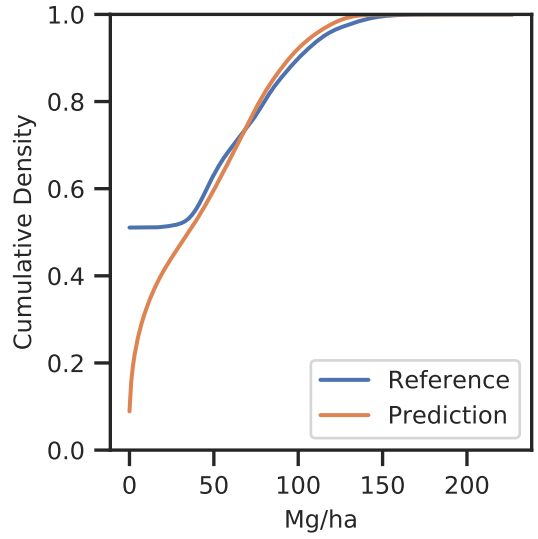


(b) Zero included

Ordinary frequency histogram (zone 41)



(a) Zero excluded



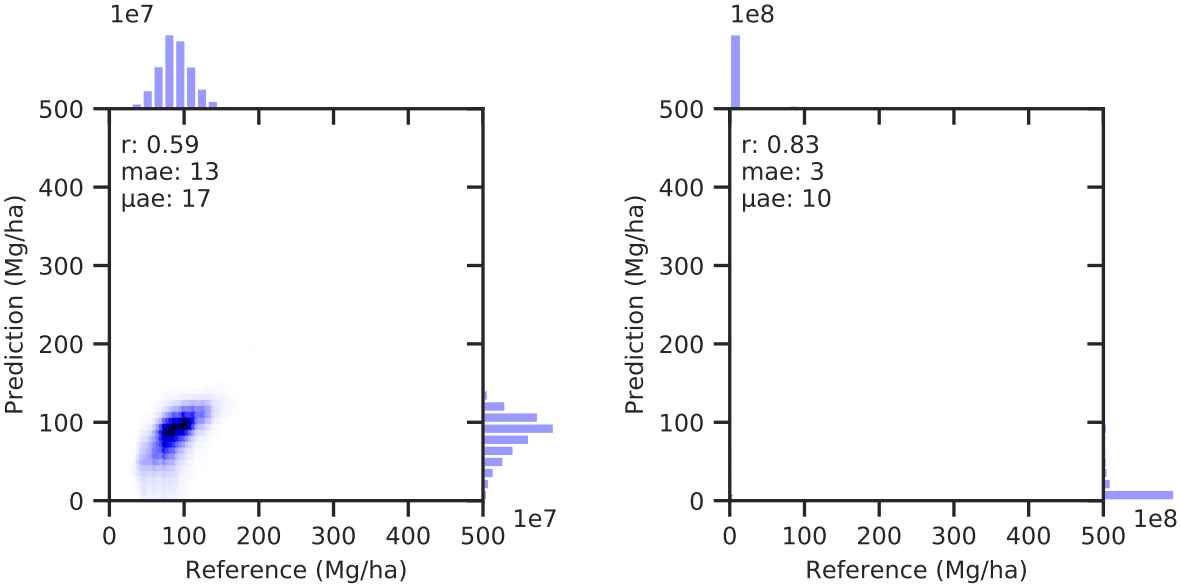
(b) Zero included

Cumulative density histogram (zone 41)

Return to zone table

Zone 42

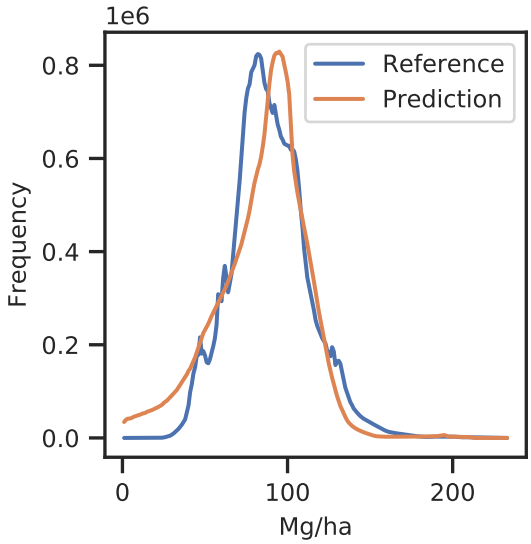
Zone map (zone 42)



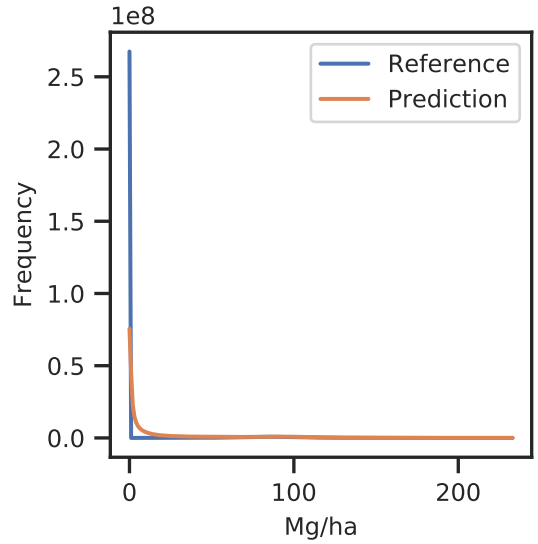
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 42)

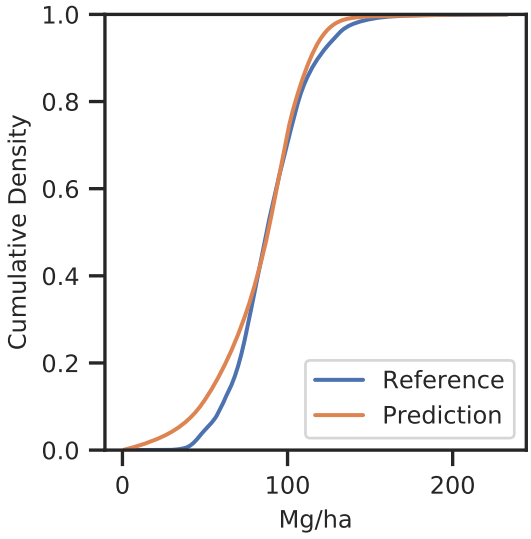


(a) Zero excluded

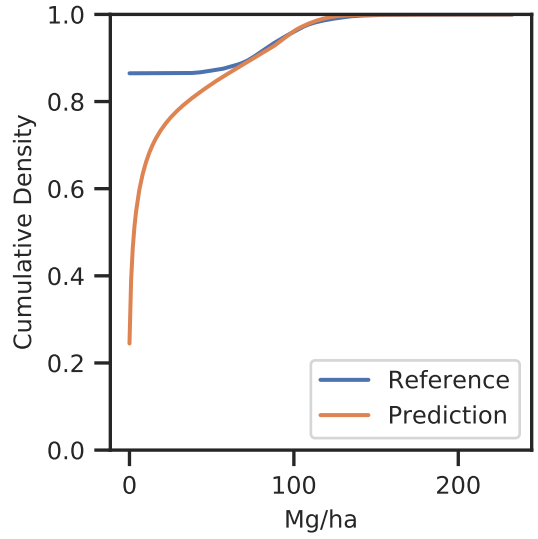


(b) Zero included

Ordinary frequency histogram (zone 42)



(a) Zero excluded

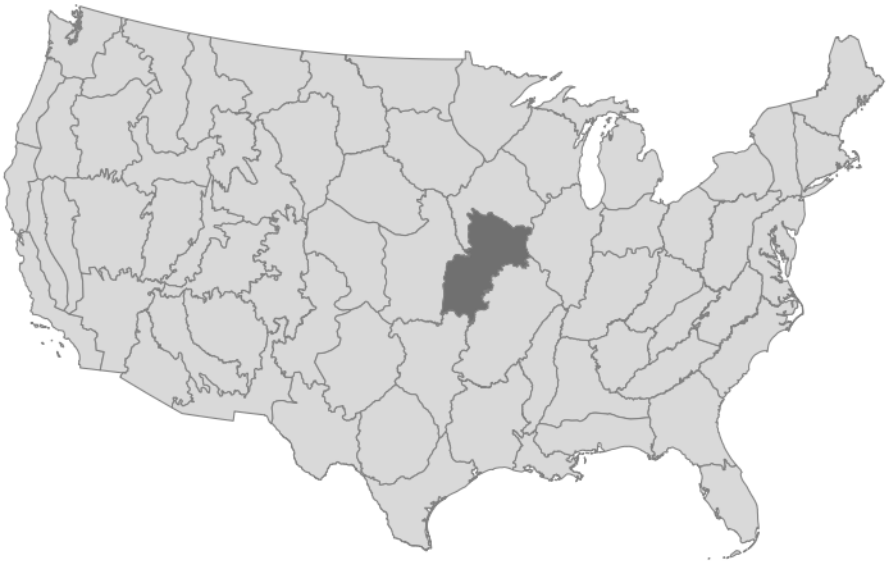


(b) Zero included

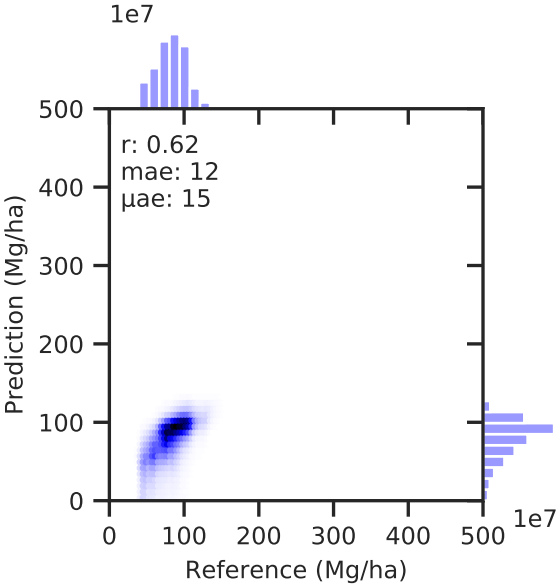
Cumulative density histogram (zone 42)

Return to zone table

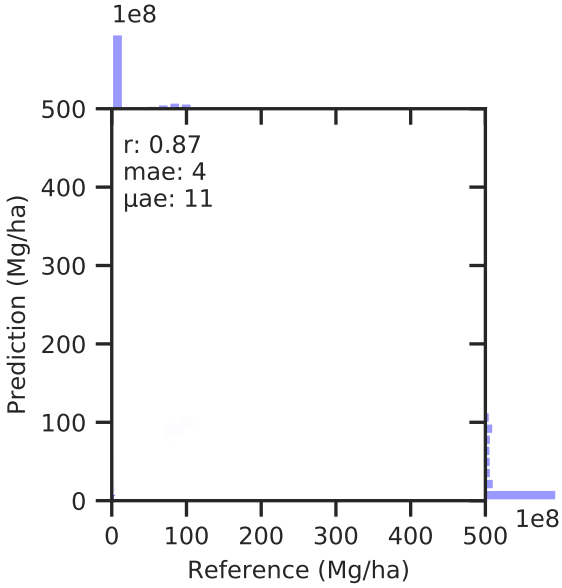
Zone 43



Zone map (zone 43)

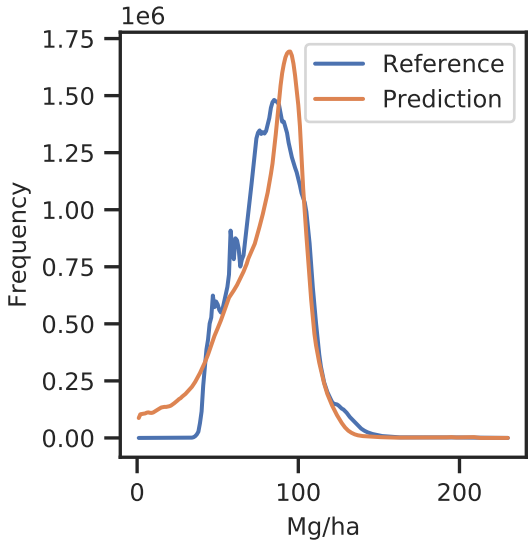


(a) Zero excluded

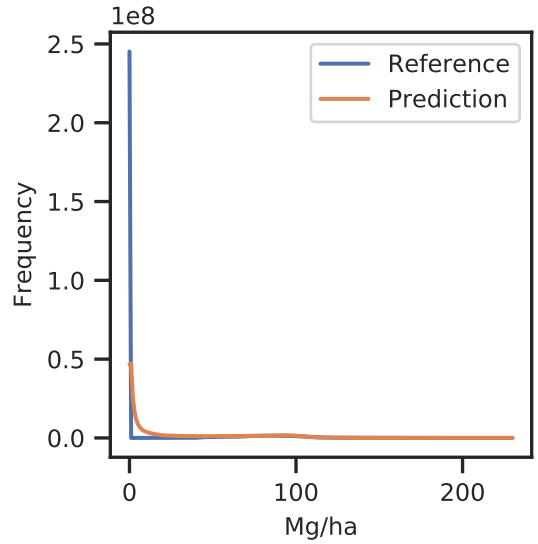


(b) Zero included

2-D frequency histogram (zone 43)

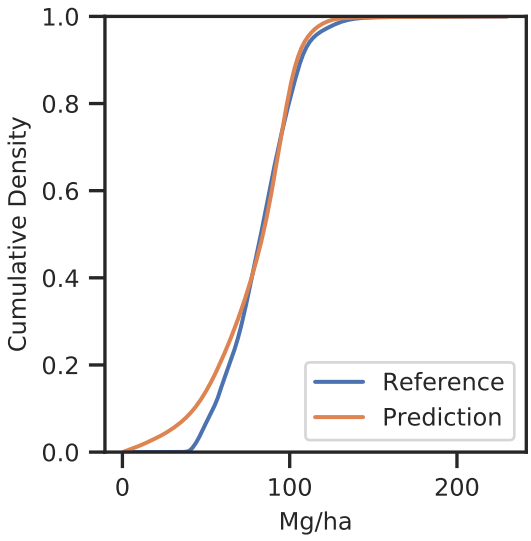


(a) Zero excluded

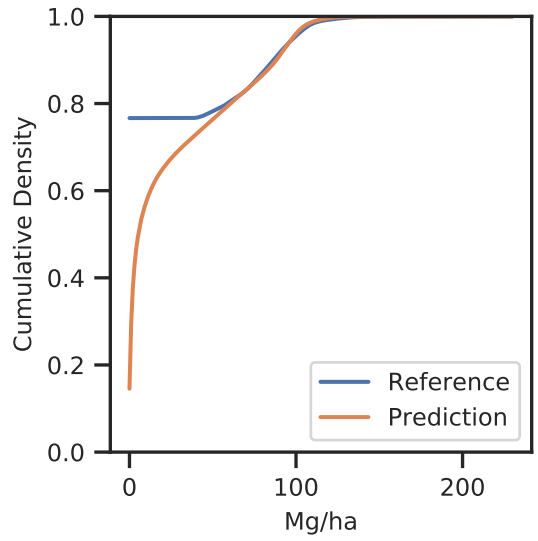


(b) Zero included

Ordinary frequency histogram (zone 43)



(a) Zero excluded

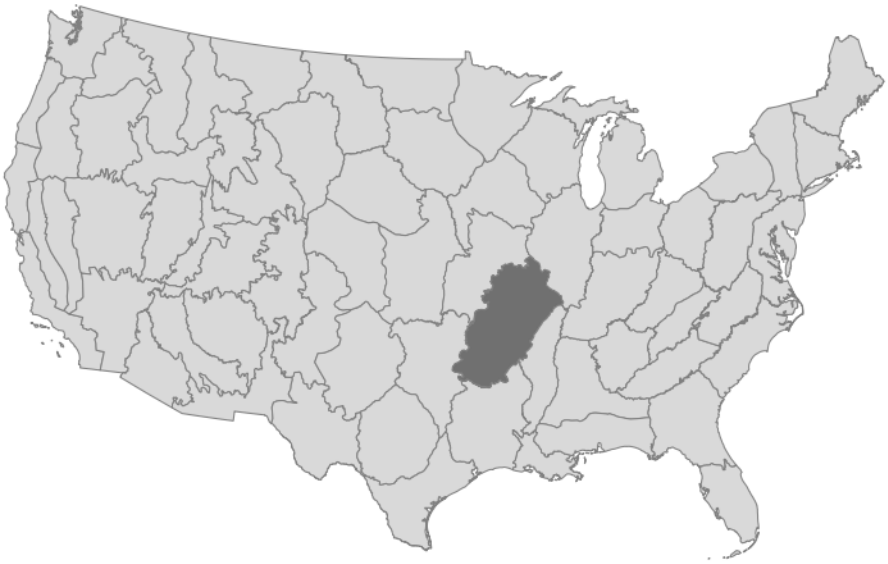


(b) Zero included

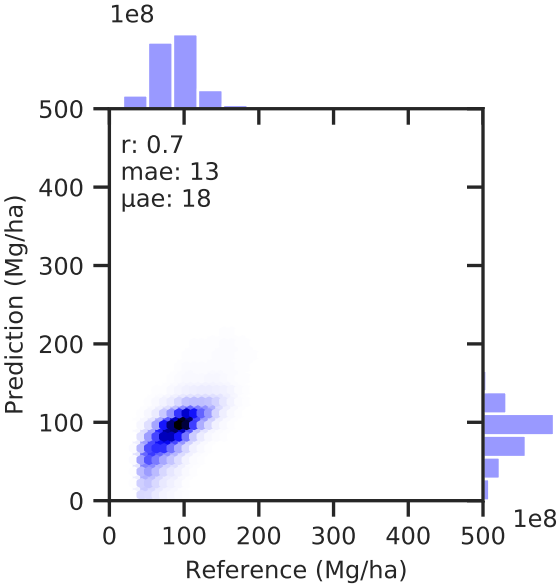
Cumulative density histogram (zone 43)

Return to zone table

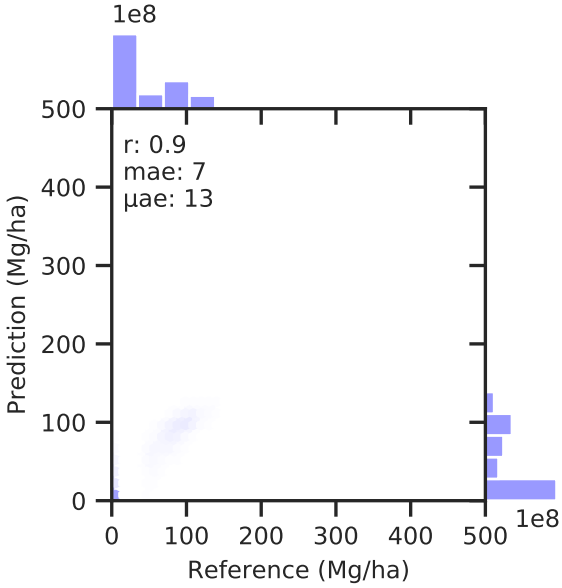
Zone 44



Zone map (zone 44)

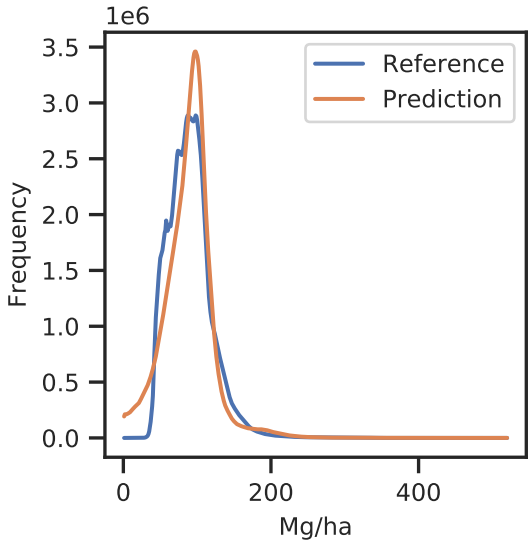


(a) Zero excluded

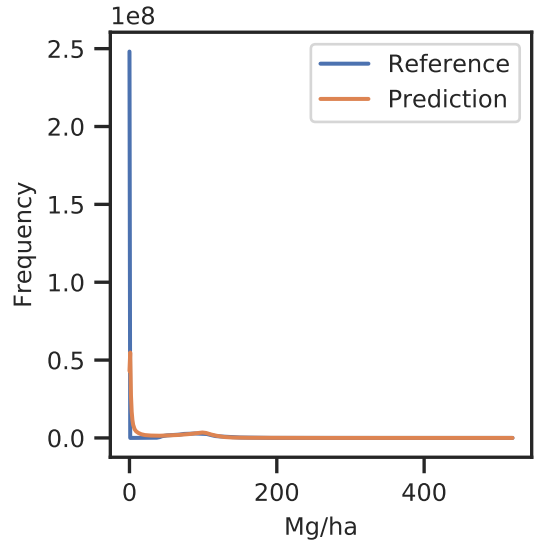


(b) Zero included

2-D frequency histogram (zone 44)

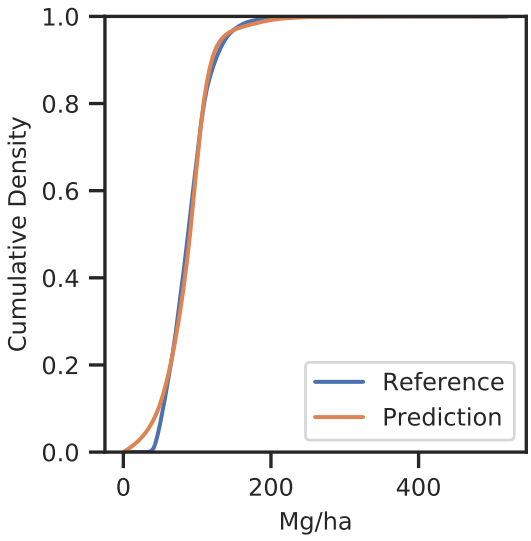


(a) Zero excluded

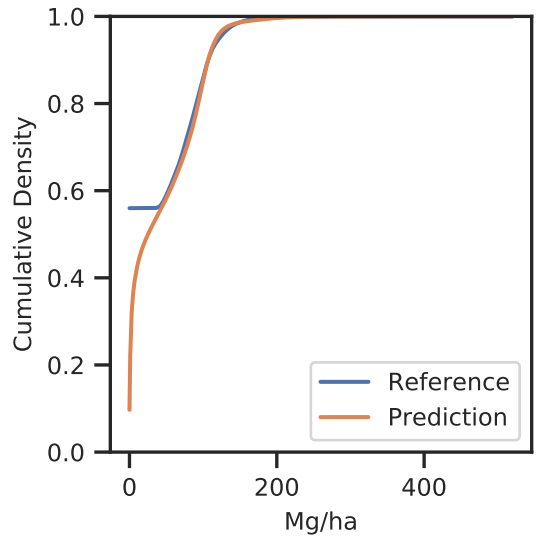


(b) Zero included

Ordinary frequency histogram (zone 44)



(a) Zero excluded



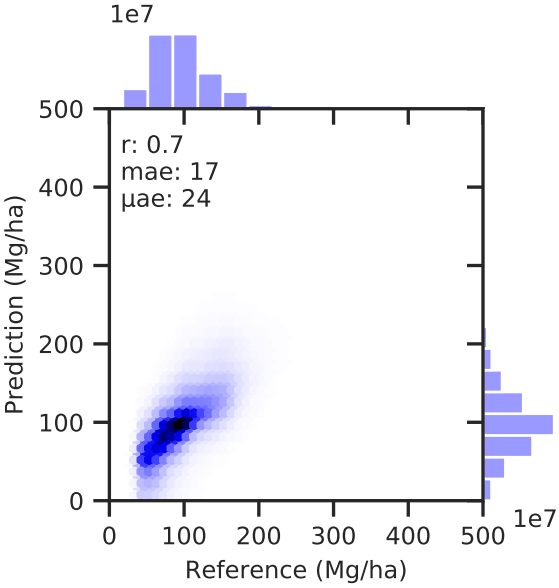
(b) Zero included

Cumulative density histogram (zone 44)

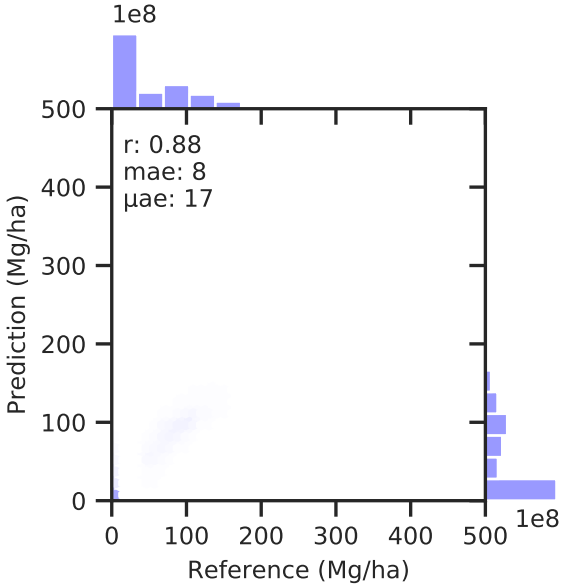
Return to zone table

Zone 45

Zone map (zone 45)

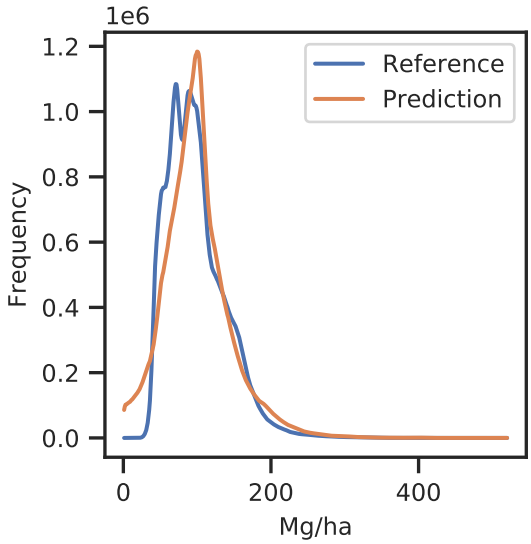


(a) Zero excluded

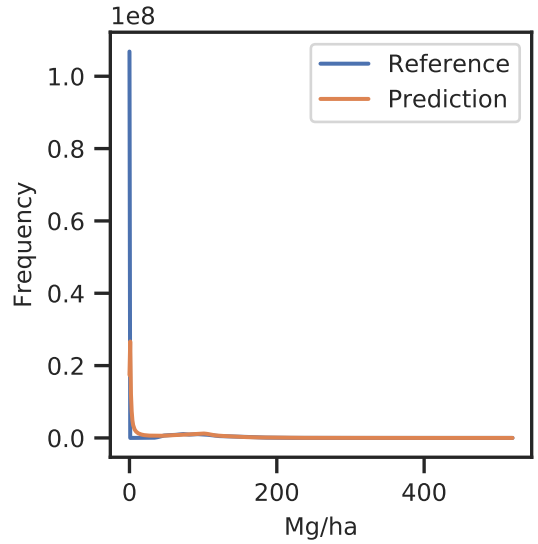


(b) Zero included

2-D frequency histogram (zone 45)

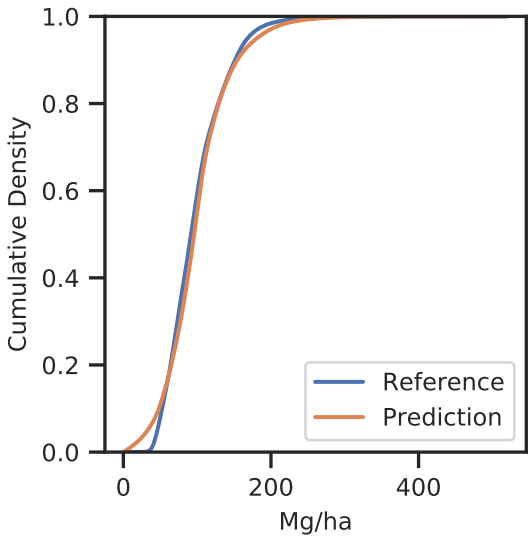


(a) Zero excluded

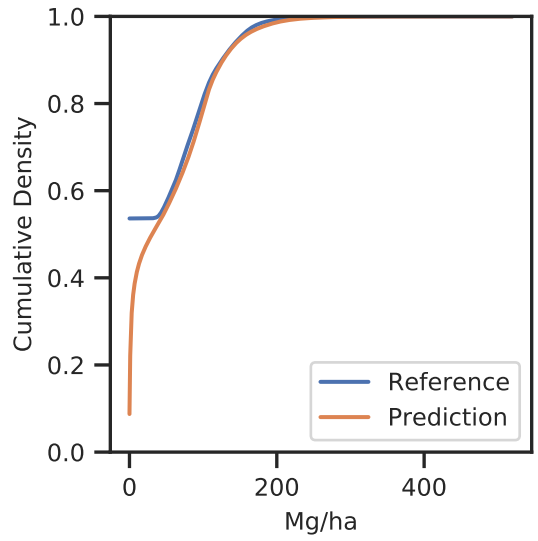


(b) Zero included

Ordinary frequency histogram (zone 45)



(a) Zero excluded



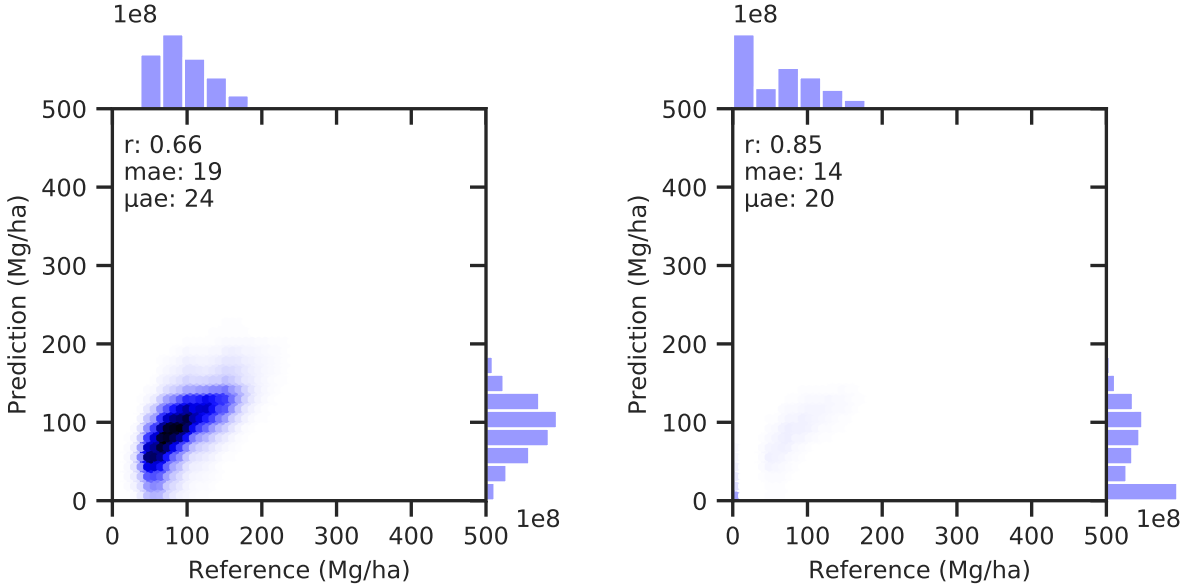
(b) Zero included

Cumulative density histogram (zone 45)

Return to zone table

Zone 46

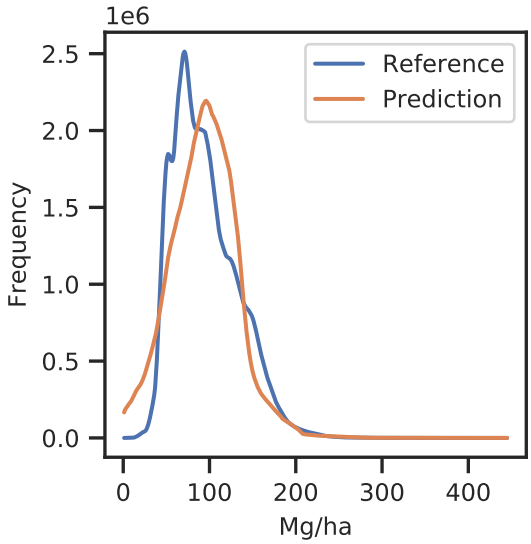
Zone map (zone 46)



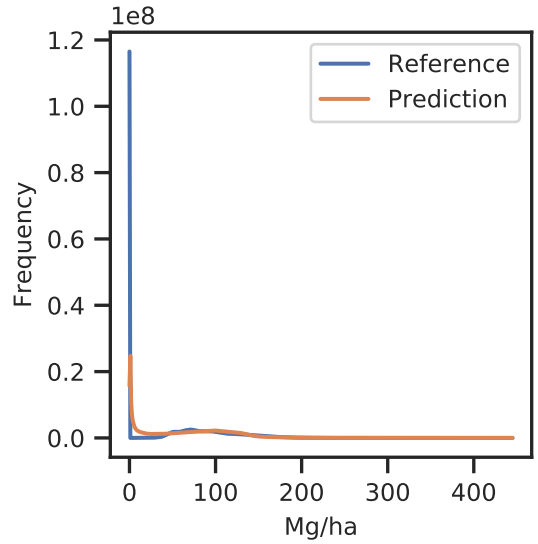
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 46)

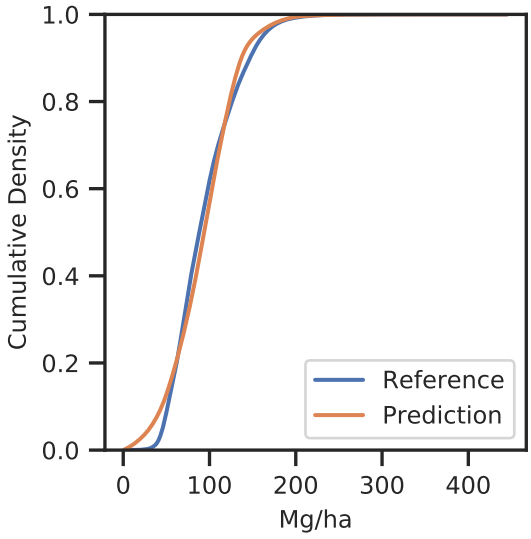


(a) Zero excluded

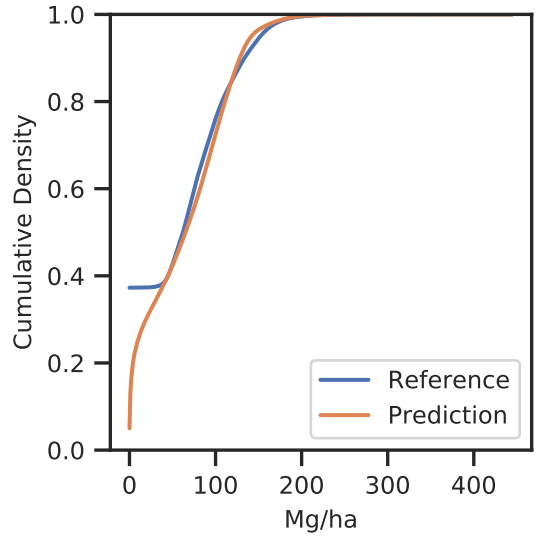


(b) Zero included

Ordinary frequency histogram (zone 46)



(a) Zero excluded

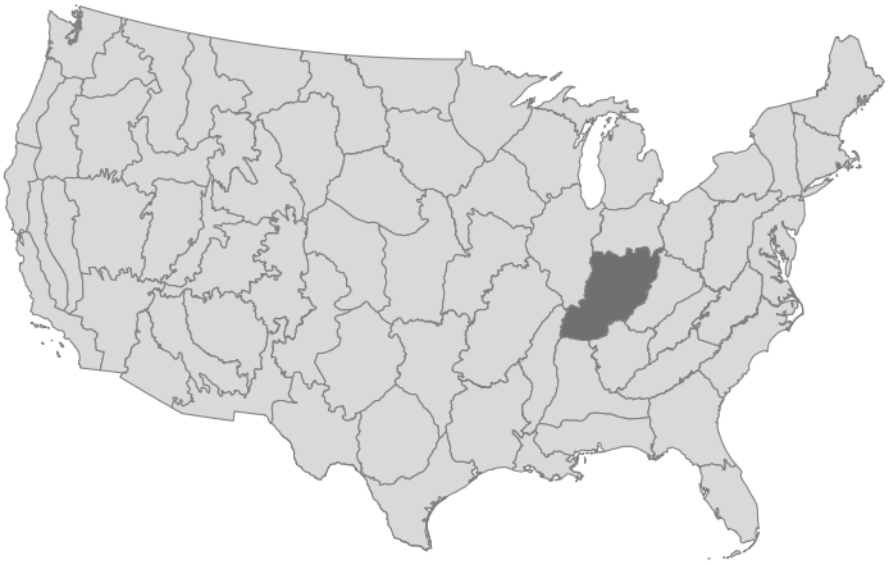


(b) Zero included

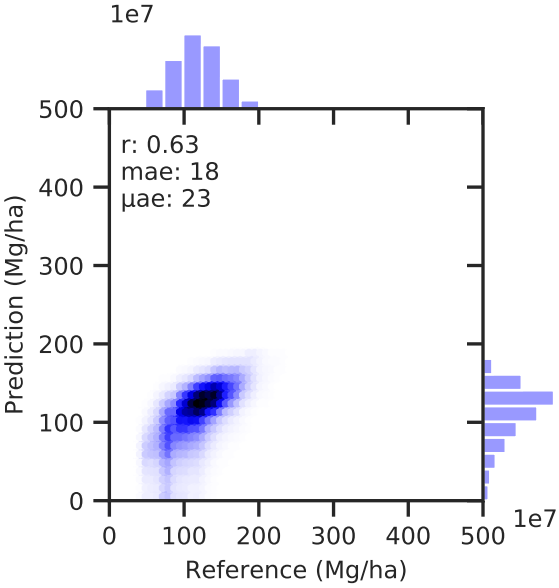
Cumulative density histogram (zone 46)

Return to zone table

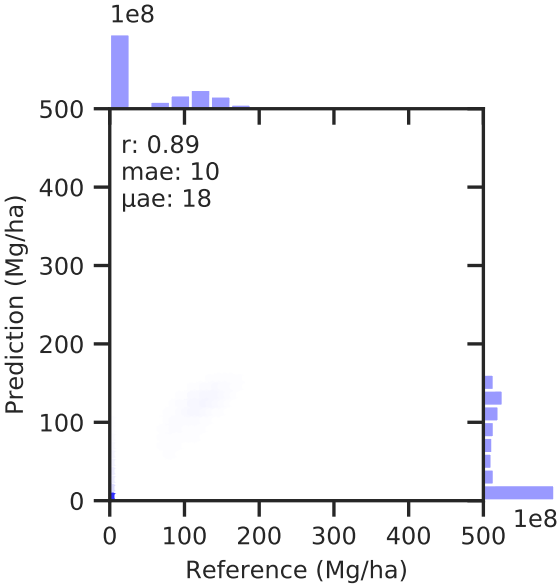
Zone 47



Zone map (zone 47)

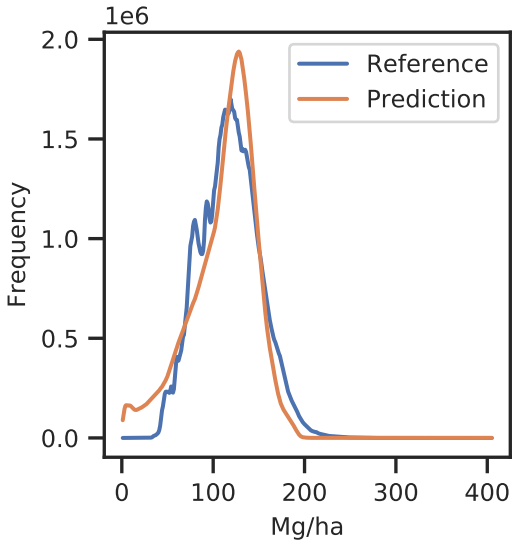


(a) Zero excluded

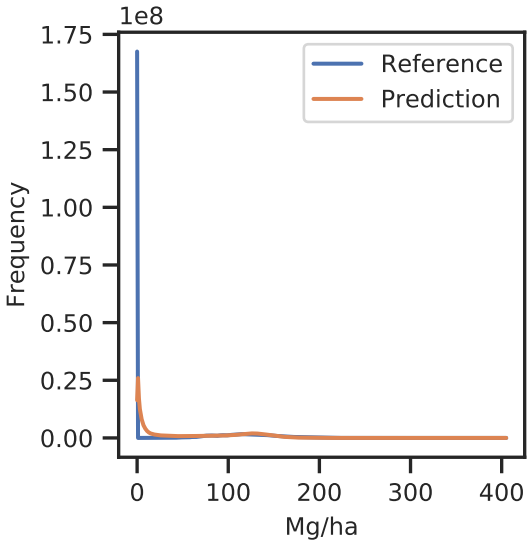


(b) Zero included

2-D frequency histogram (zone 47)

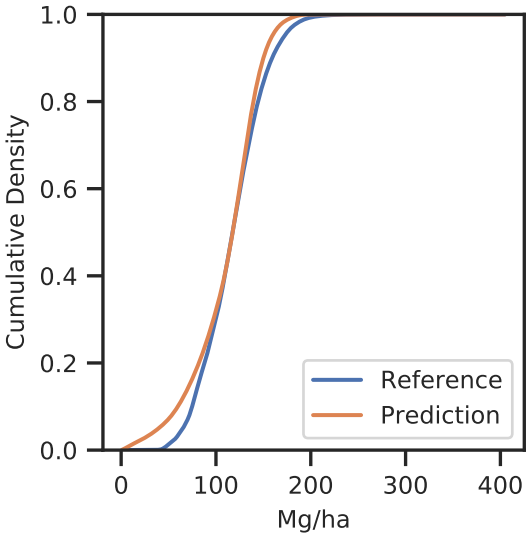


(a) Zero excluded

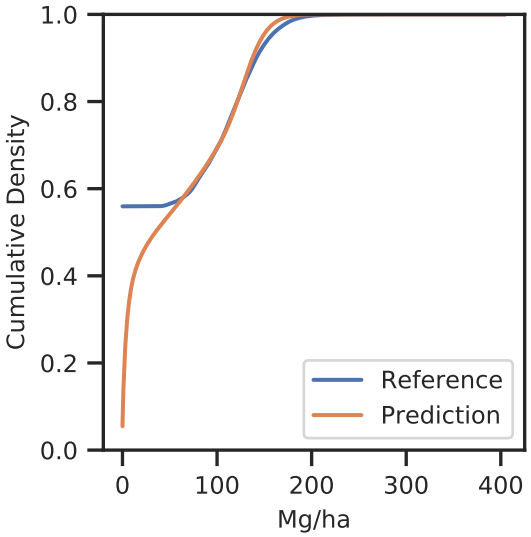


(b) Zero included

Ordinary frequency histogram (zone 47)



(a) Zero excluded



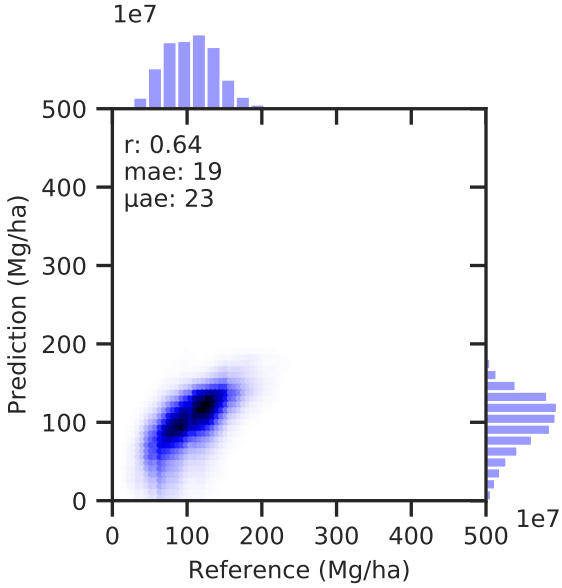
(b) Zero included

Cumulative density histogram (zone 47)

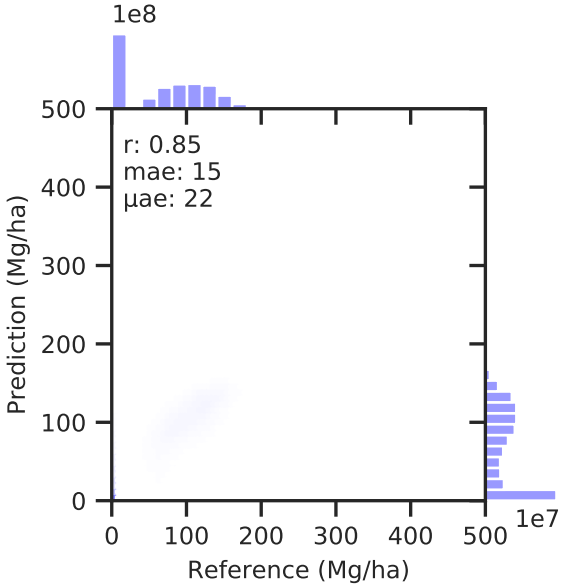
Return to zone table

Zone 48

Zone map (zone 48)

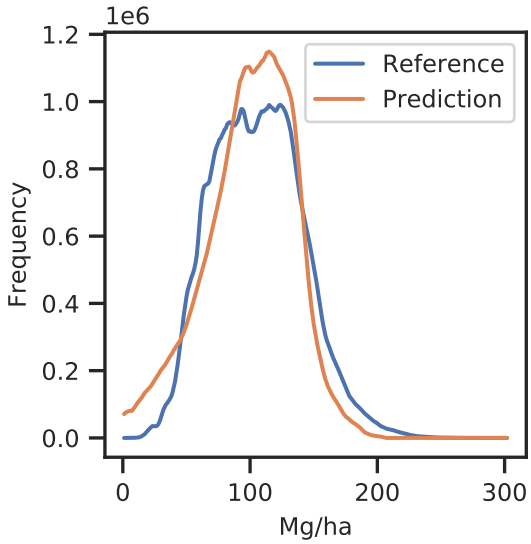


(a) Zero excluded

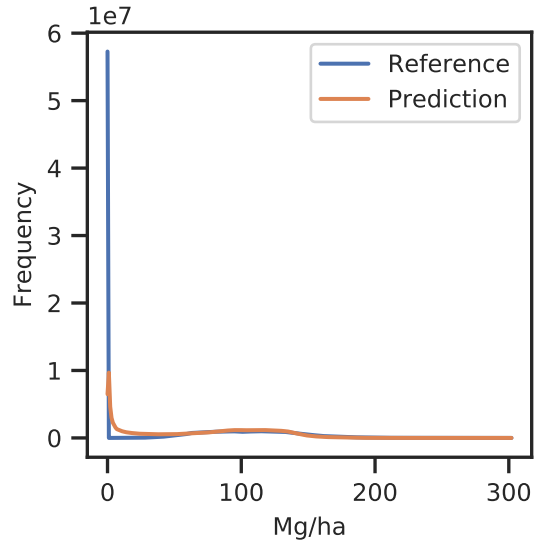


(b) Zero included

2-D frequency histogram (zone 48)

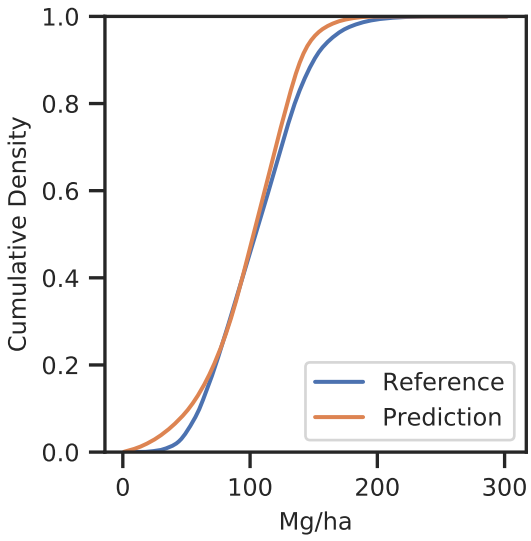


(a) Zero excluded

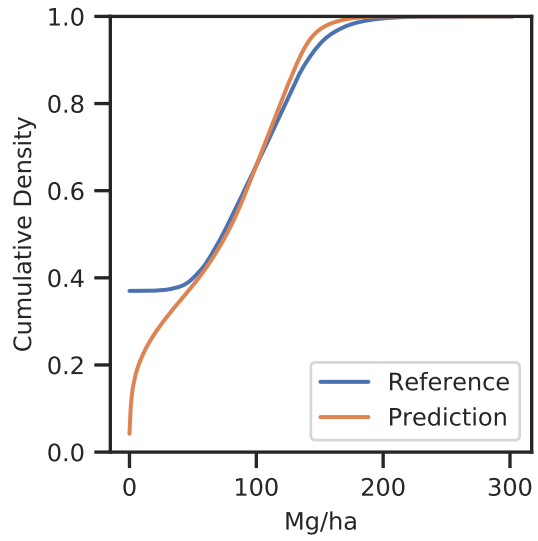


(b) Zero included

Ordinary frequency histogram (zone 48)



(a) Zero excluded



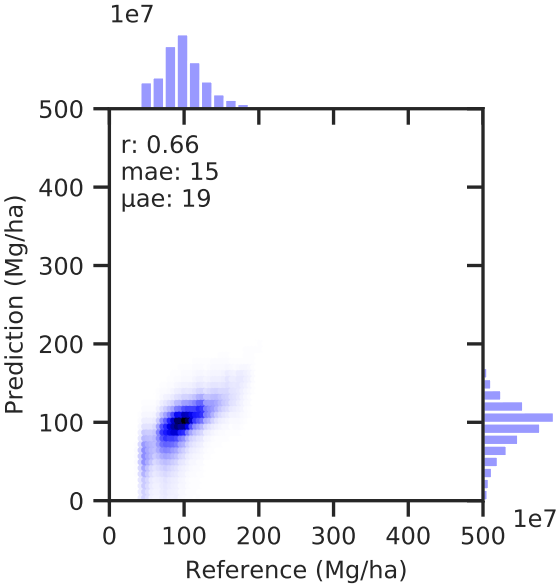
(b) Zero included

Cumulative density histogram (zone 48)

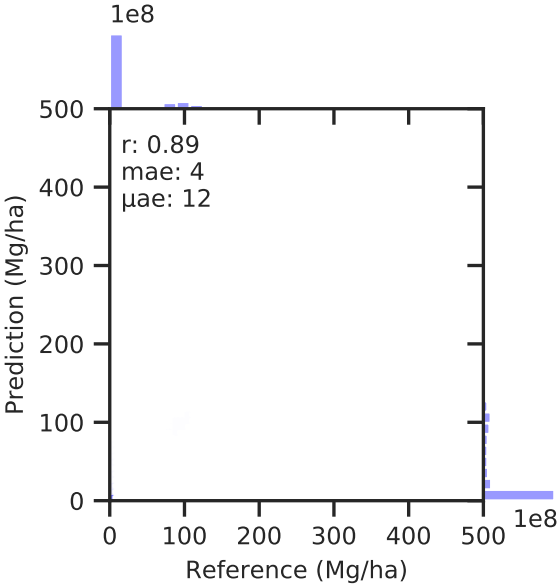
Return to zone table

Zone 49

Zone map (zone 49)

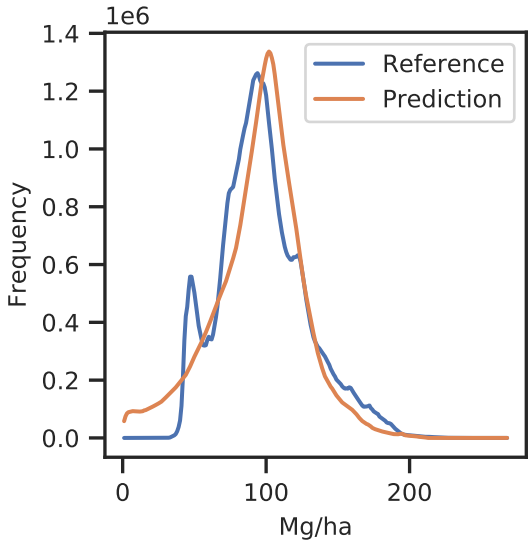


(a) Zero excluded

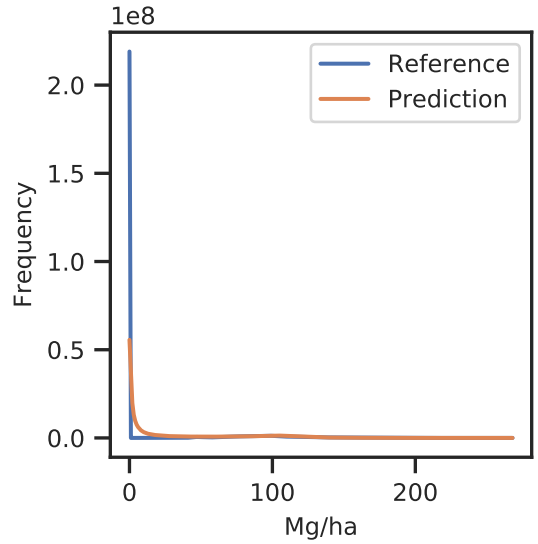


(b) Zero included

2-D frequency histogram (zone 49)

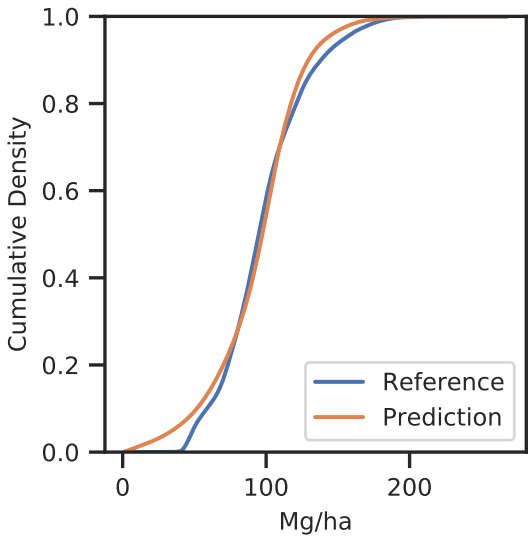


(a) Zero excluded

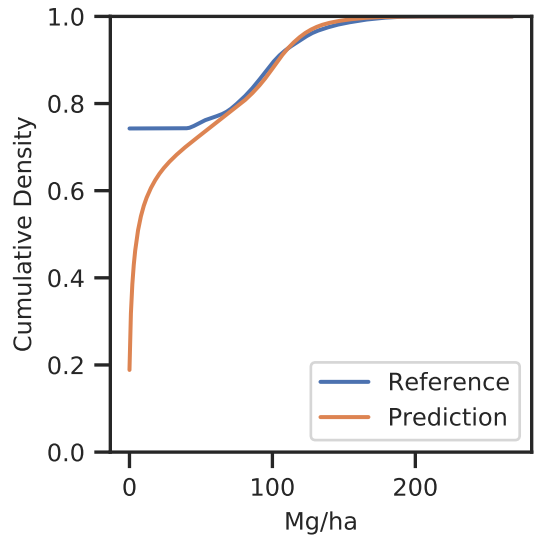


(b) Zero included

Ordinary frequency histogram (zone 49)



(a) Zero excluded

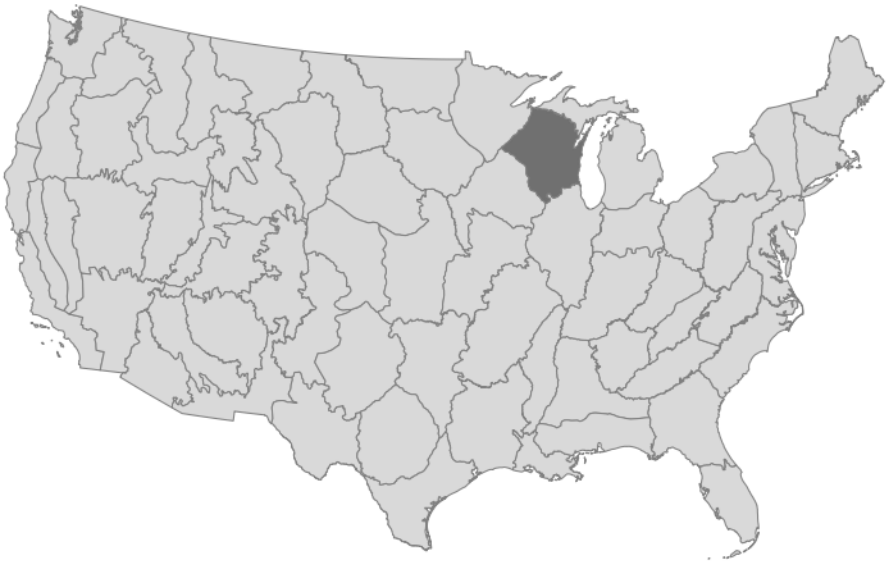


(b) Zero included

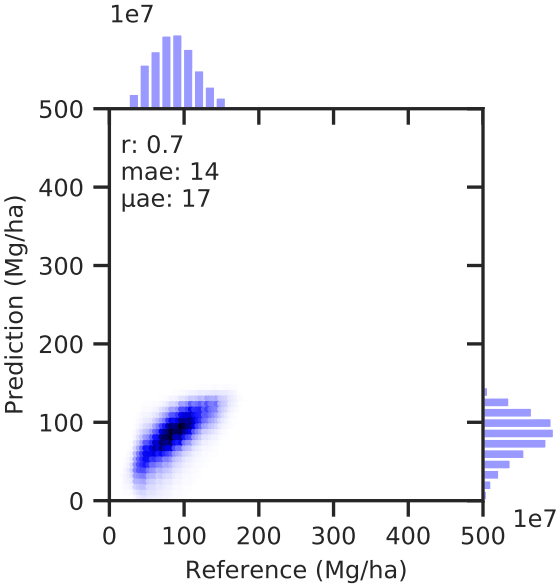
Cumulative density histogram (zone 49)

Return to zone table

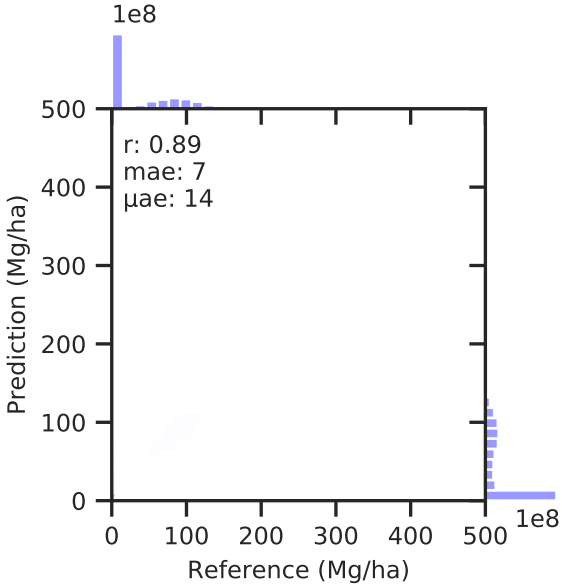
Zone 50



Zone map (zone 50)

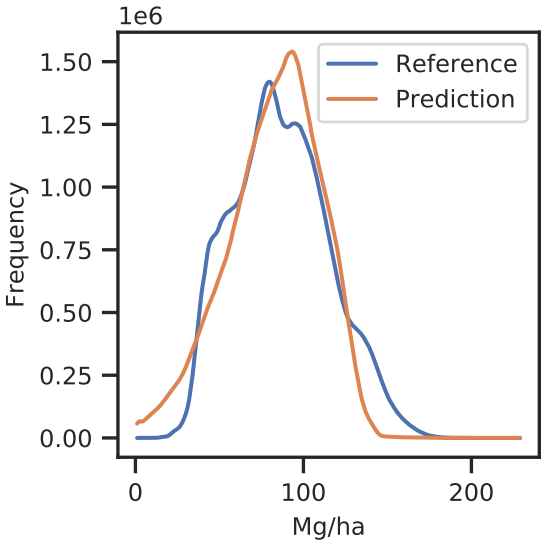


(a) Zero excluded

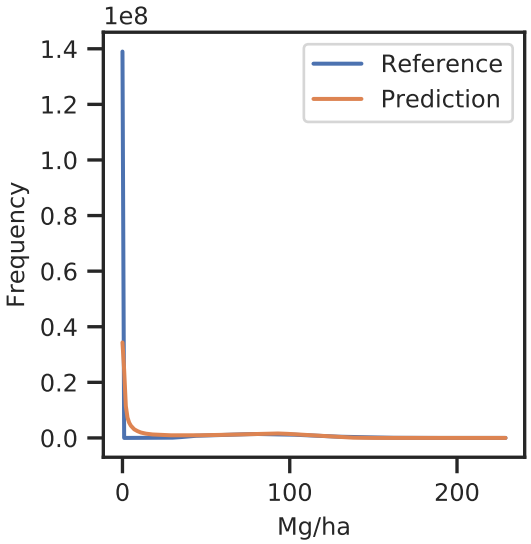


(b) Zero included

2-D frequency histogram (zone 50)

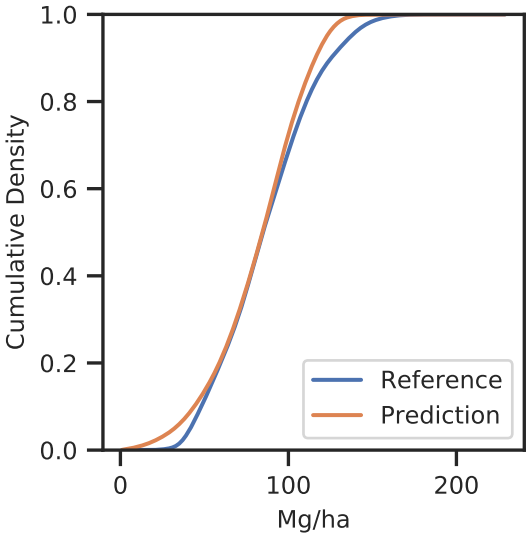


(a) Zero excluded

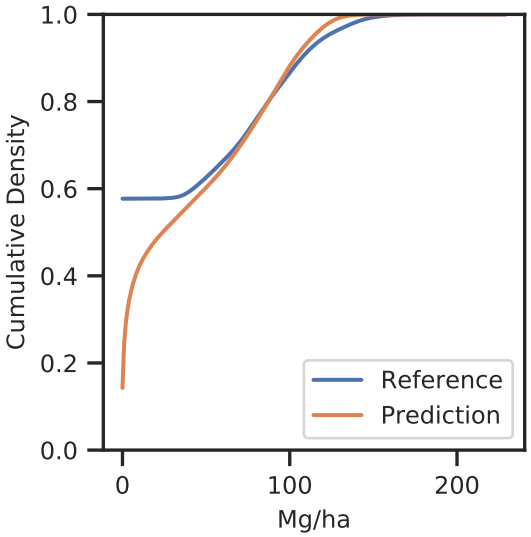


(b) Zero included

Ordinary frequency histogram (zone 50)



(a) Zero excluded



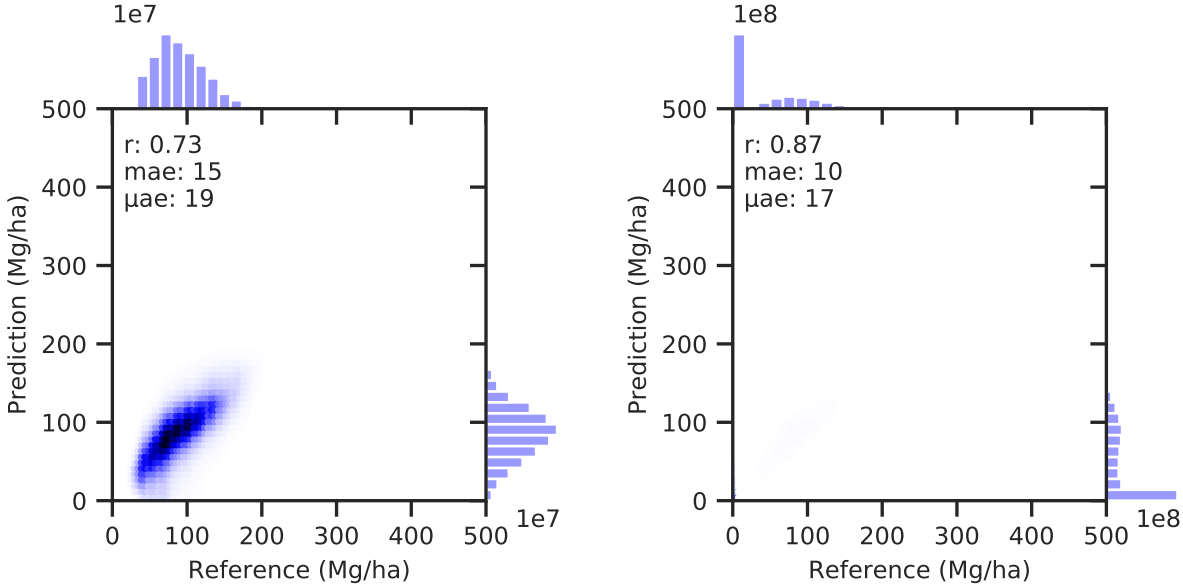
(b) Zero included

Cumulative density histogram (zone 50)

Return to zone table

Zone 51

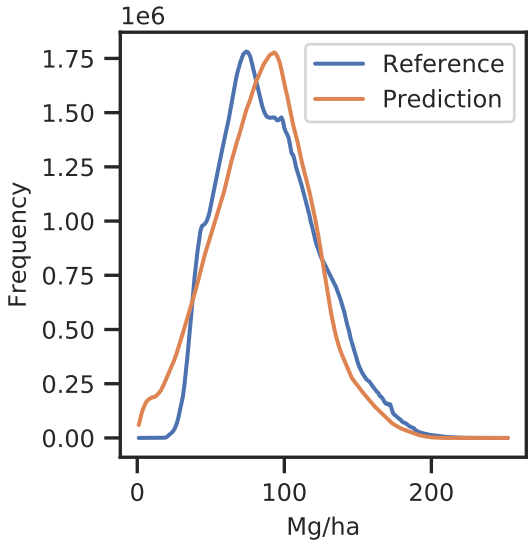
Zone map (zone 51)



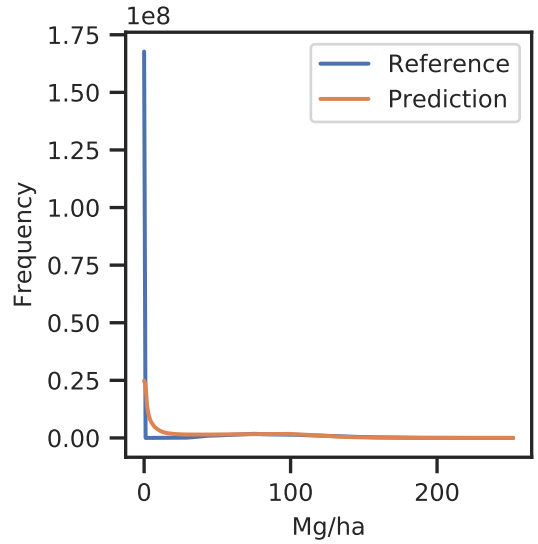
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 51)

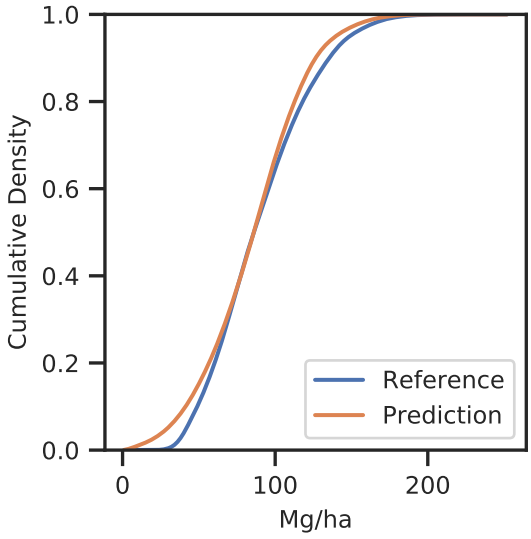


(a) Zero excluded

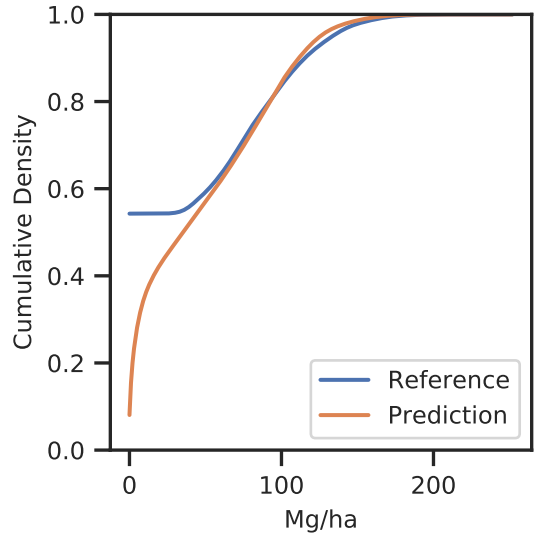


(b) Zero included

Ordinary frequency histogram (zone 51)



(a) Zero excluded



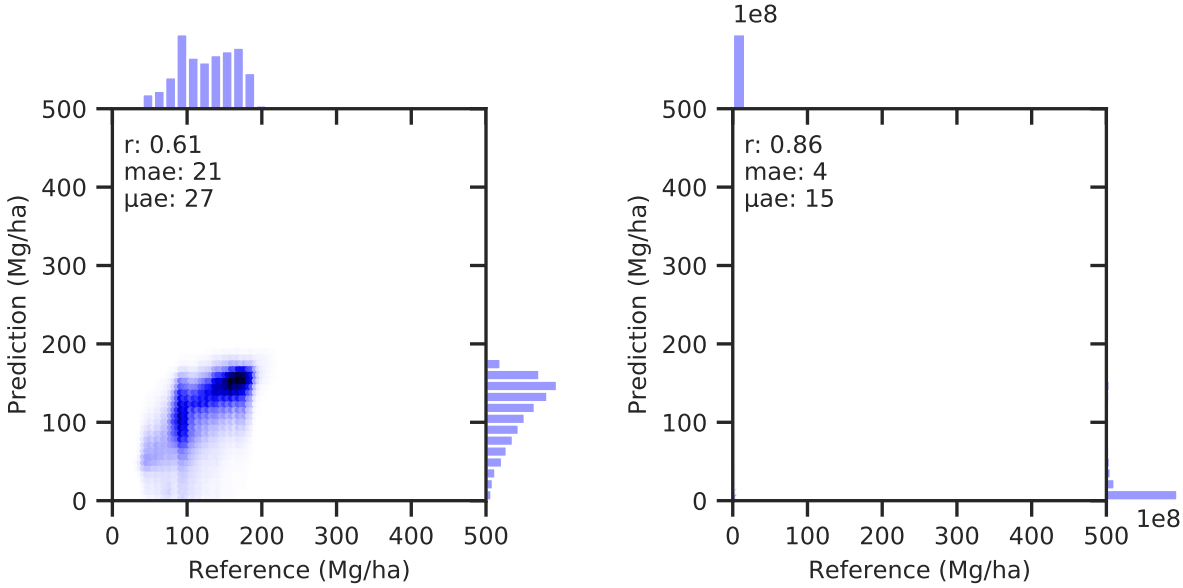
(b) Zero included

Cumulative density histogram (zone 51)

Return to zone table

Zone 52

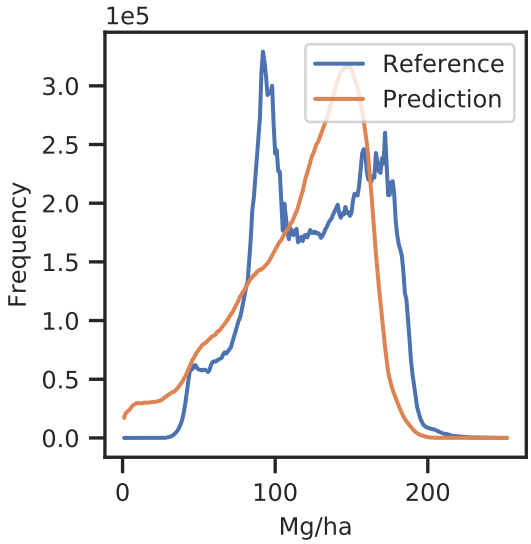
Zone map (zone 52)



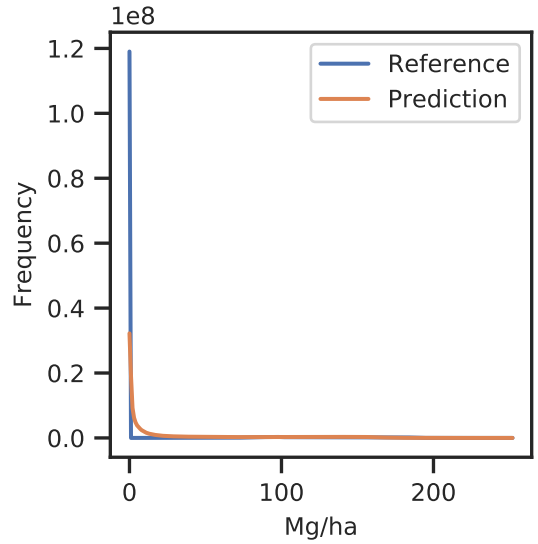
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 52)

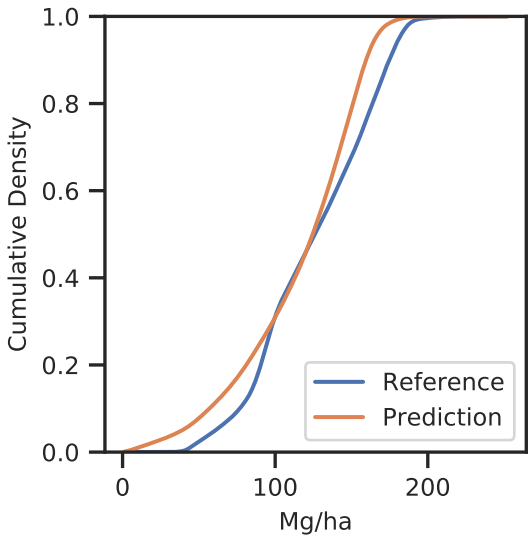


(a) Zero excluded

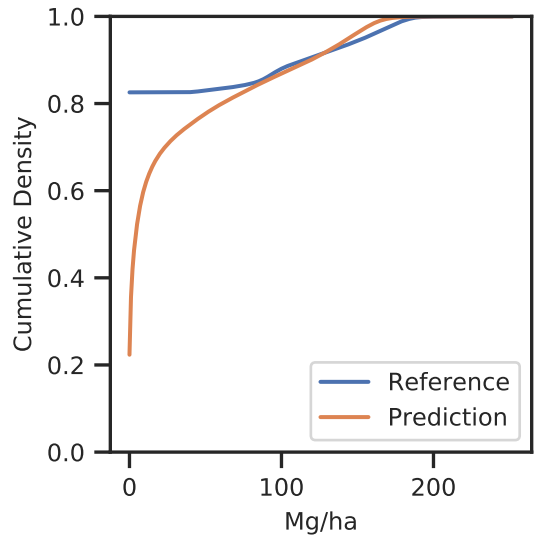


(b) Zero included

Ordinary frequency histogram (zone 52)



(a) Zero excluded

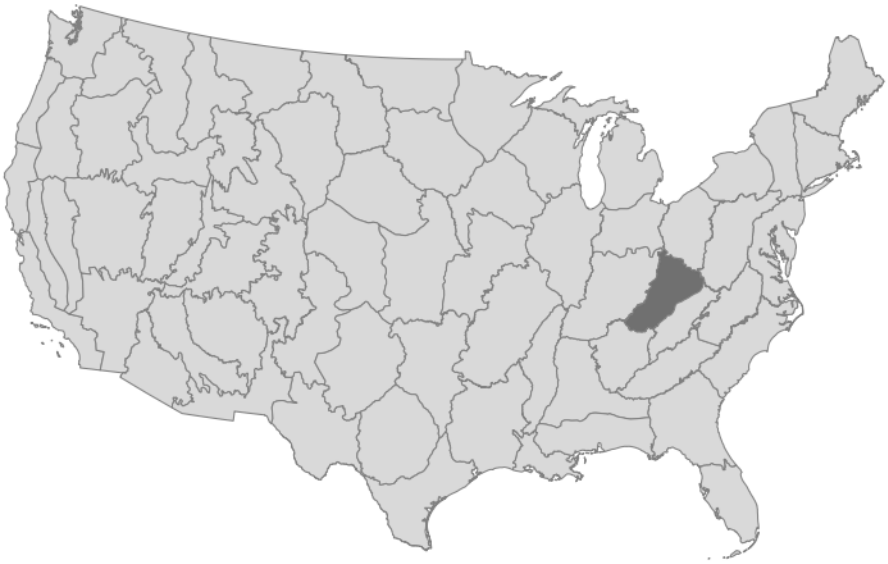


(b) Zero included

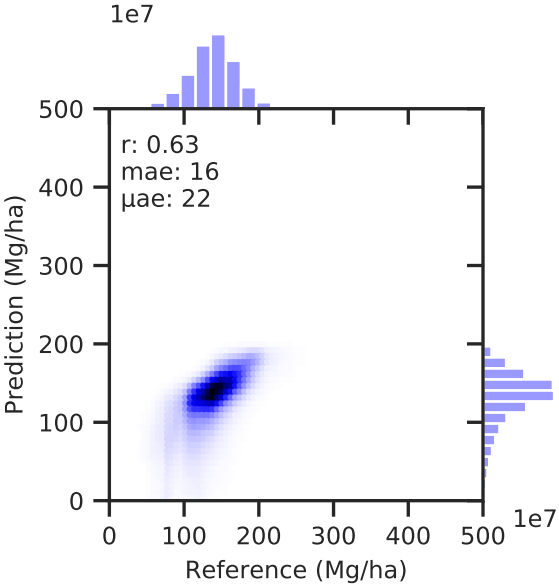
Cumulative density histogram (zone 52)

Return to zone table

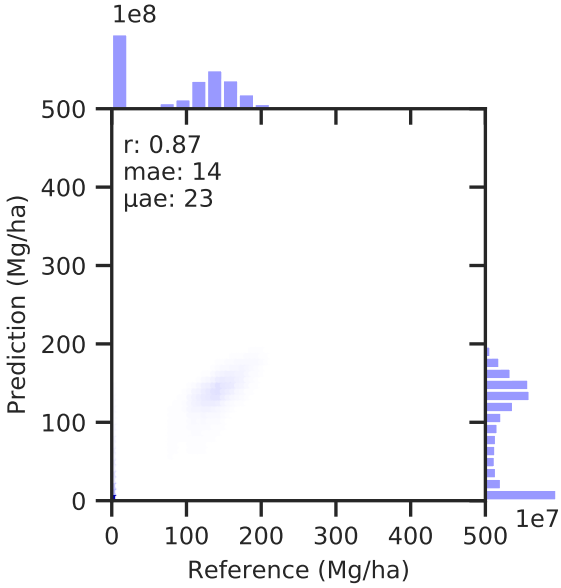
Zone 53



Zone map (zone 53)

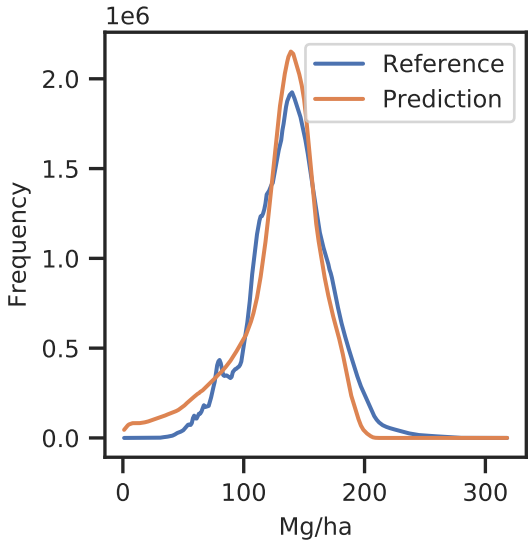


(a) Zero excluded

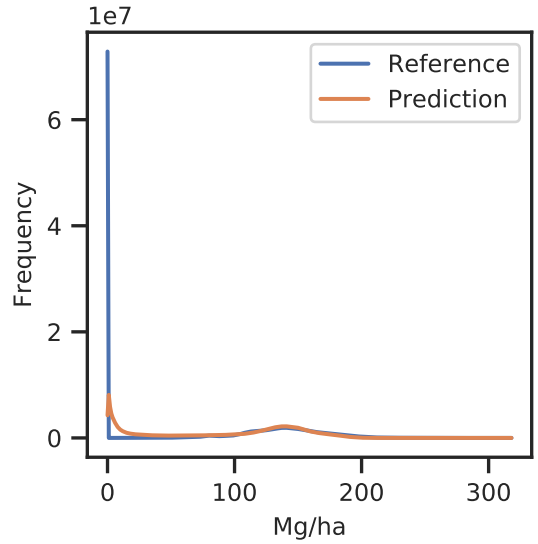


(b) Zero included

2-D frequency histogram (zone 53)

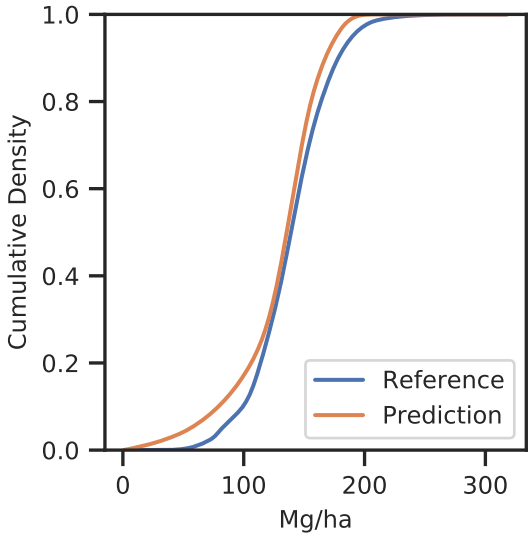


(a) Zero excluded

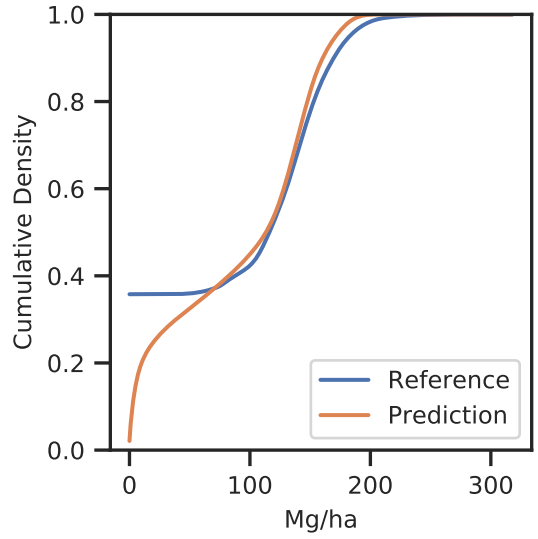


(b) Zero included

Ordinary frequency histogram (zone 53)



(a) Zero excluded



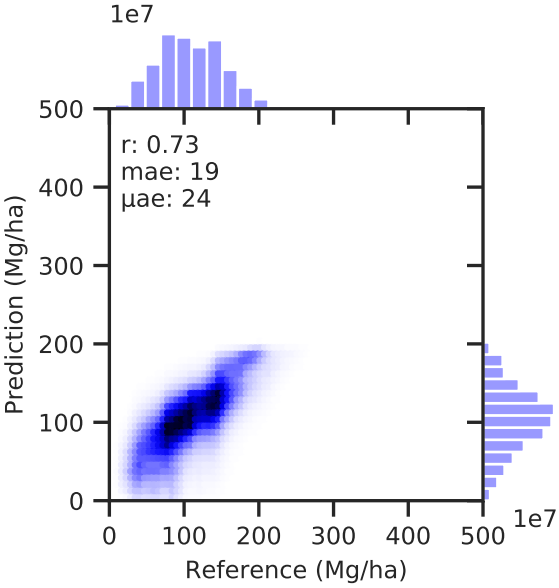
(b) Zero included

Cumulative density histogram (zone 53)

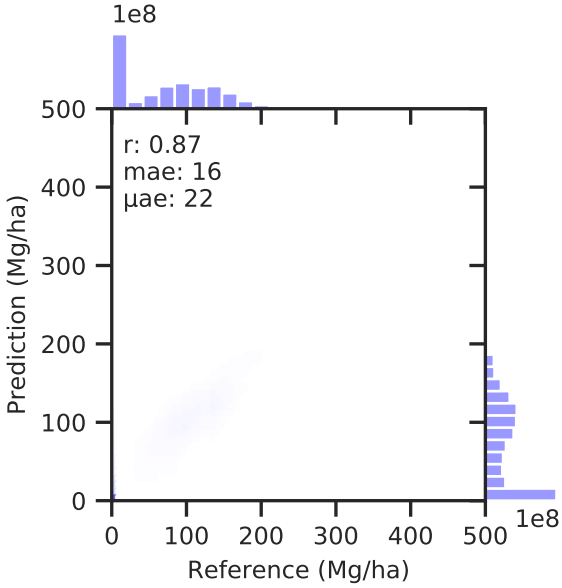
Return to zone table

Zone 54

Zone map (zone 54)

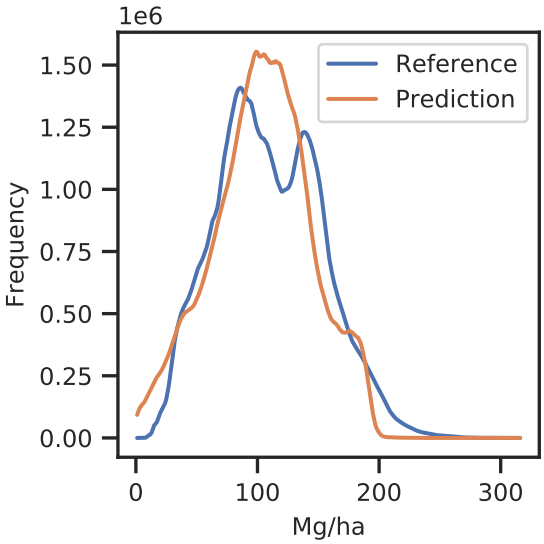


(a) Zero excluded

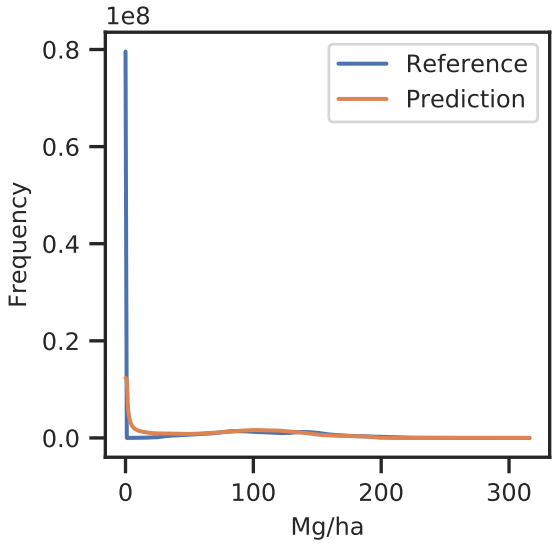


(b) Zero included

2-D frequency histogram (zone 54)

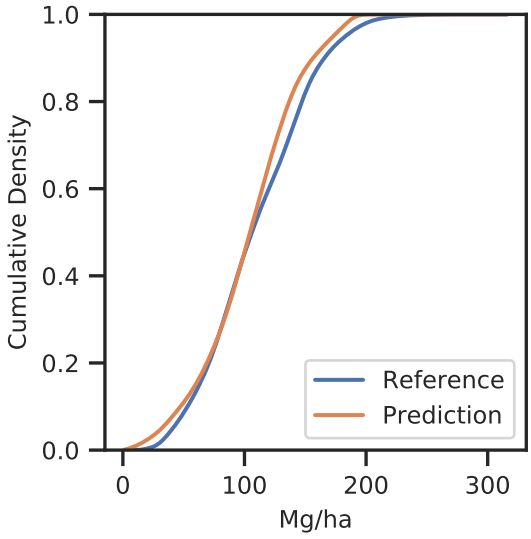


(a) Zero excluded

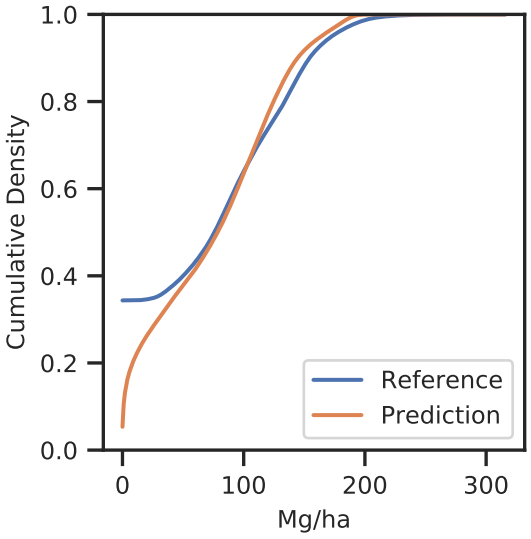


(b) Zero included

Ordinary frequency histogram (zone 54)



(a) Zero excluded



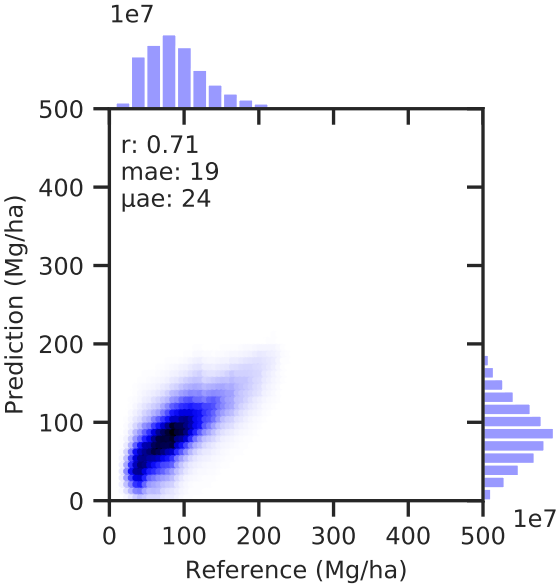
(b) Zero included

Cumulative density histogram (zone 54)

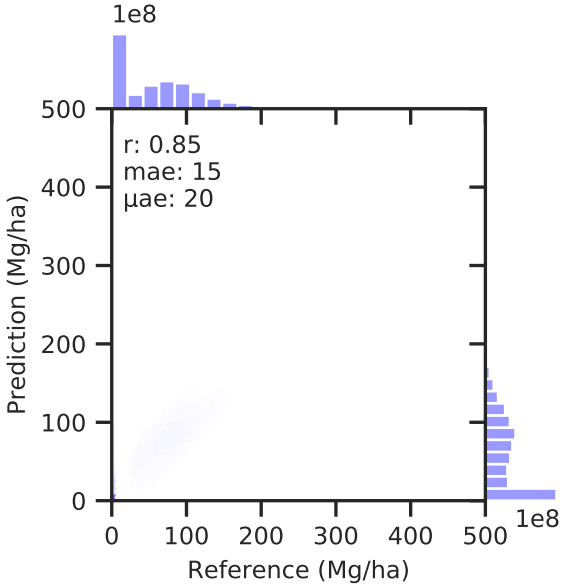
Return to zone table

Zone 55

Zone map (zone 55)

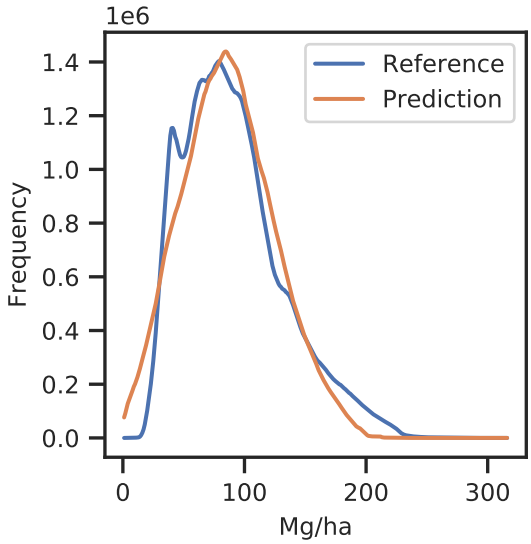


(a) Zero excluded

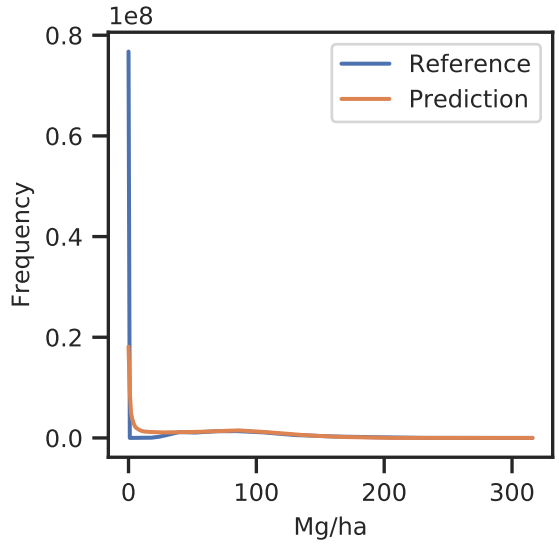


(b) Zero included

2-D frequency histogram (zone 55)

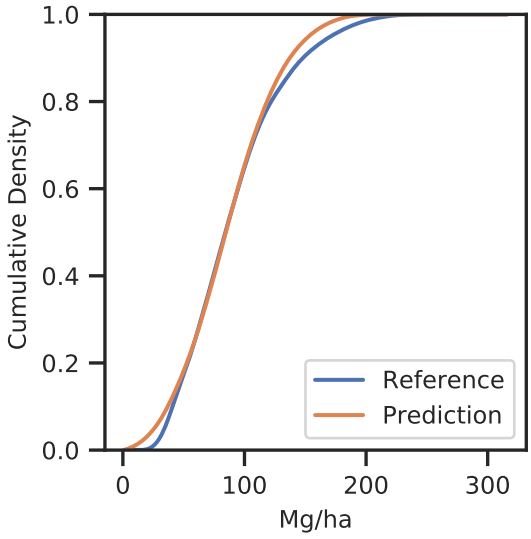


(a) Zero excluded

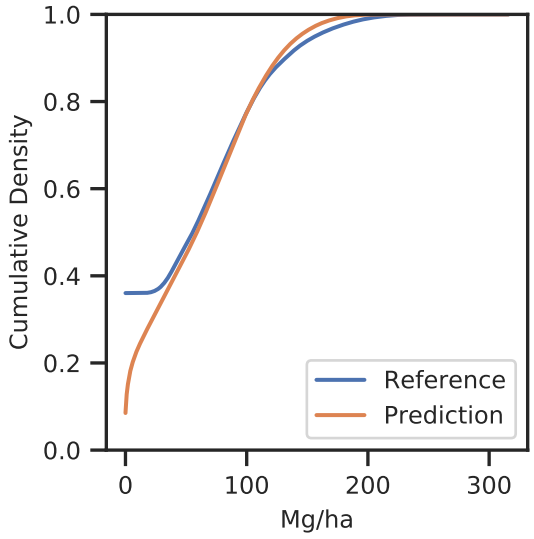


(b) Zero included

Ordinary frequency histogram (zone 55)



(a) Zero excluded



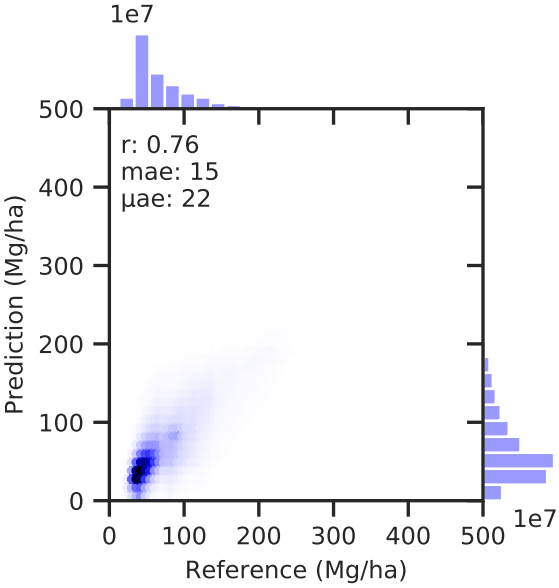
(b) Zero included

Cumulative density histogram (zone 55)

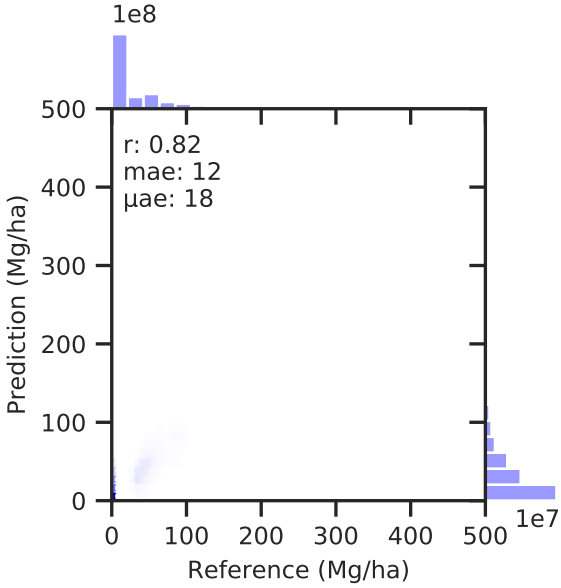
Return to zone table

Zone 56

Zone map (zone 56)

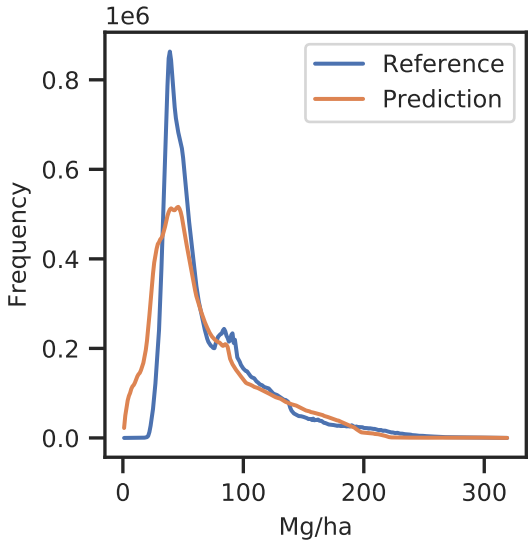


(a) Zero excluded

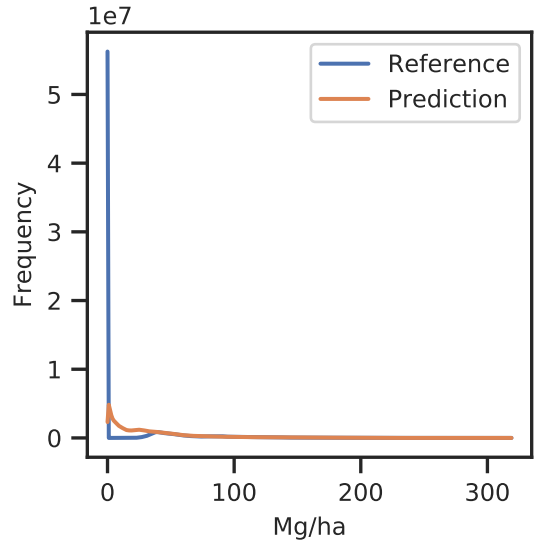


(b) Zero included

2-D frequency histogram (zone 56)

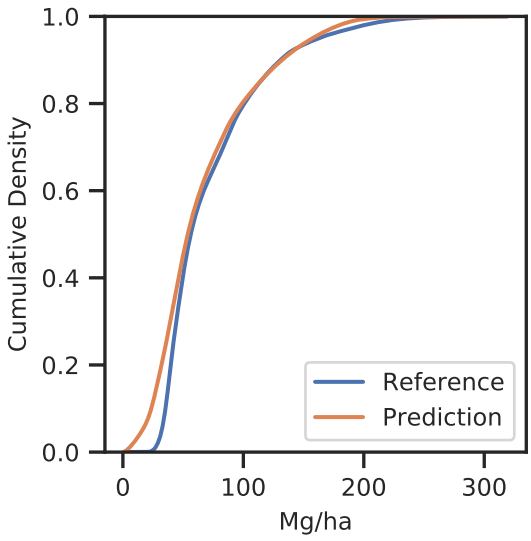


(a) Zero excluded

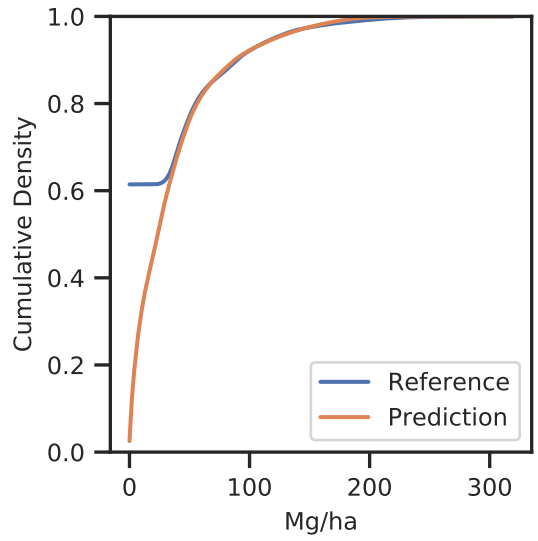


(b) Zero included

Ordinary frequency histogram (zone 56)



(a) Zero excluded



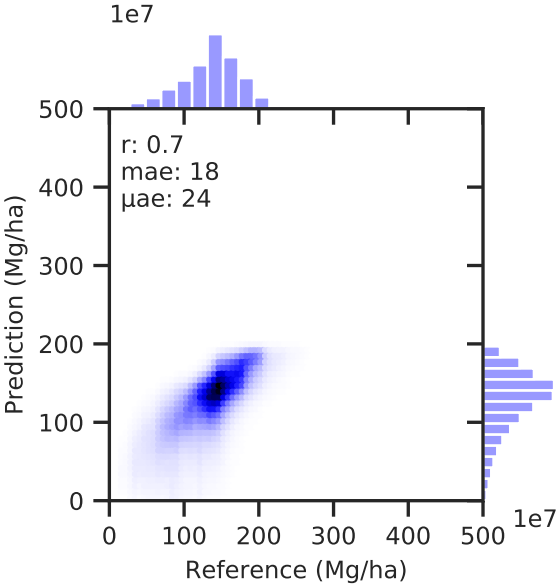
(b) Zero included

Cumulative density histogram (zone 56)

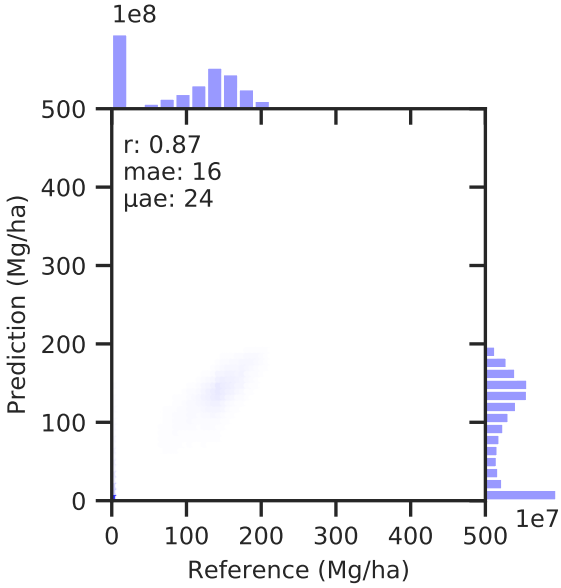
Return to zone table

Zone 57

Zone map (zone 57)

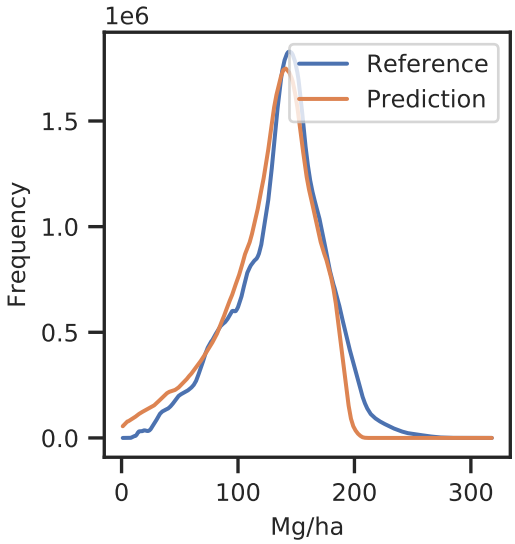


(a) Zero excluded

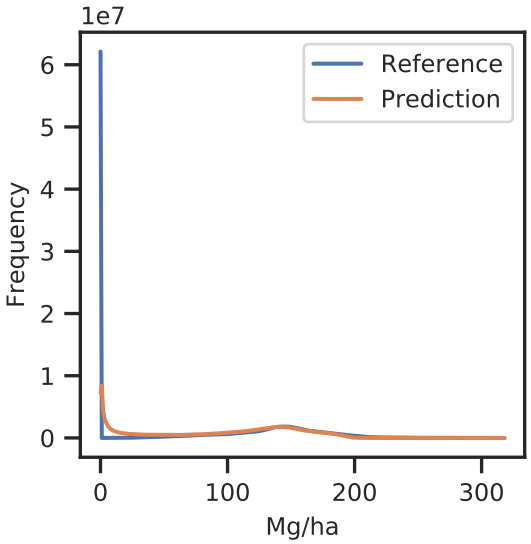


(b) Zero included

2-D frequency histogram (zone 57)

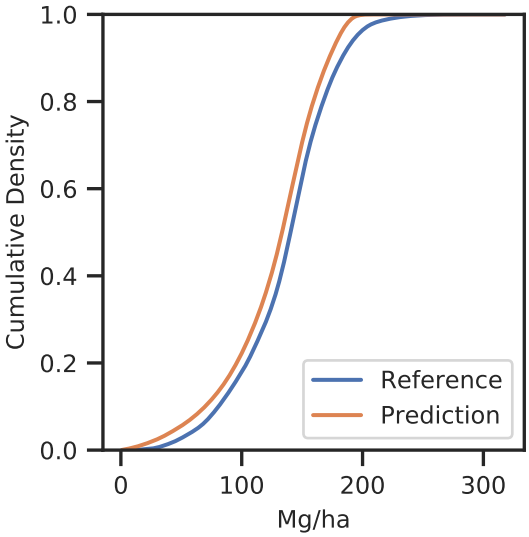


(a) Zero excluded

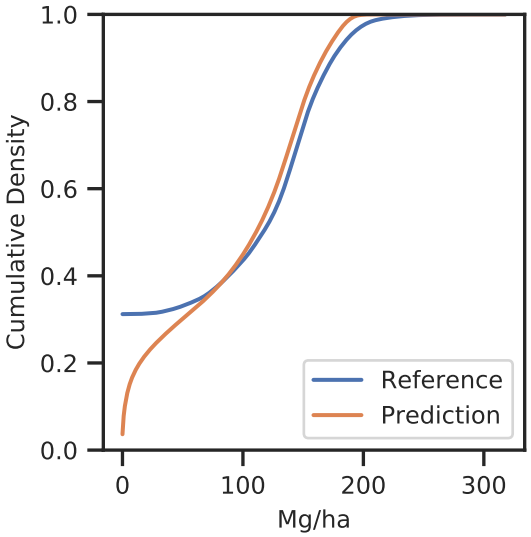


(b) Zero included

Ordinary frequency histogram (zone 57)



(a) Zero excluded



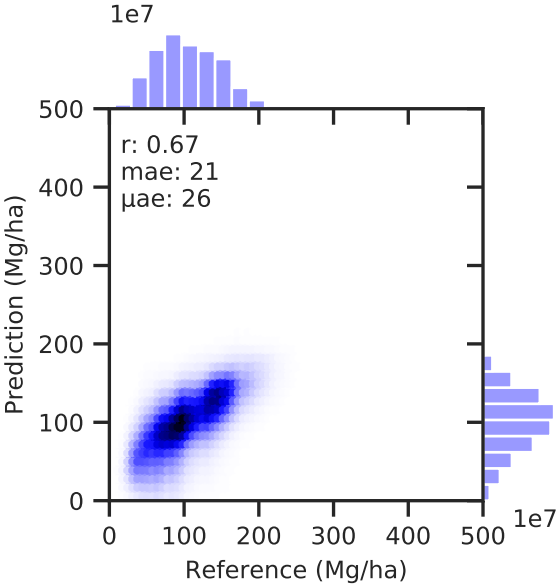
(b) Zero included

Cumulative density histogram (zone 57)

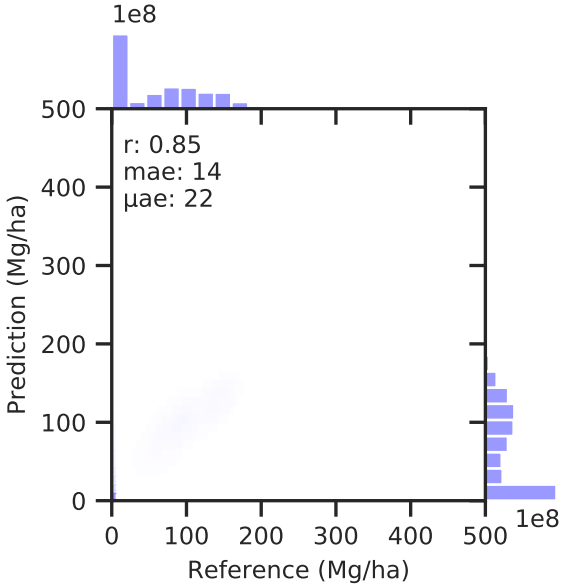
Return to zone table

Zone 58

Zone map (zone 58)

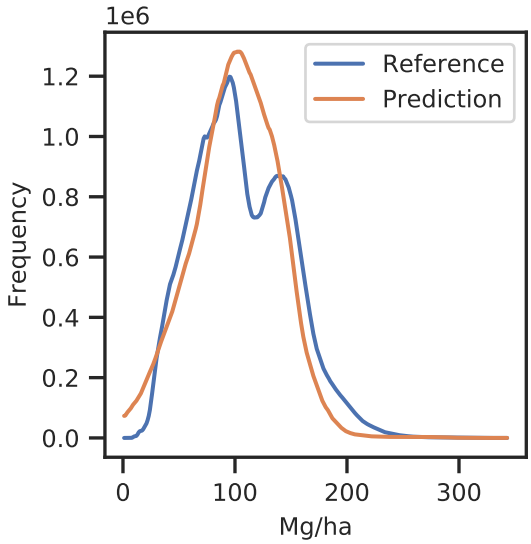


(a) Zero excluded

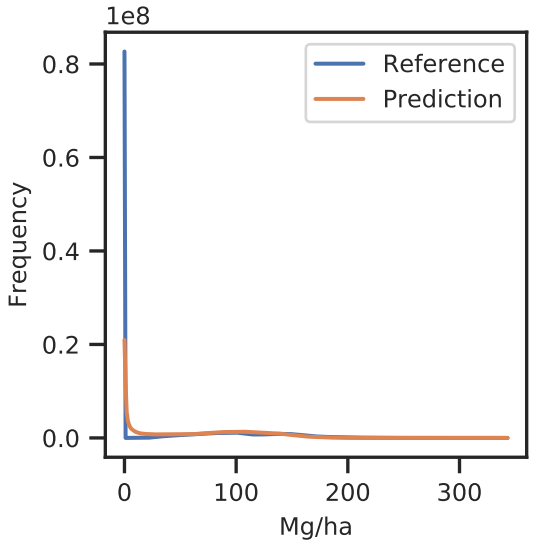


(b) Zero included

2-D frequency histogram (zone 58)

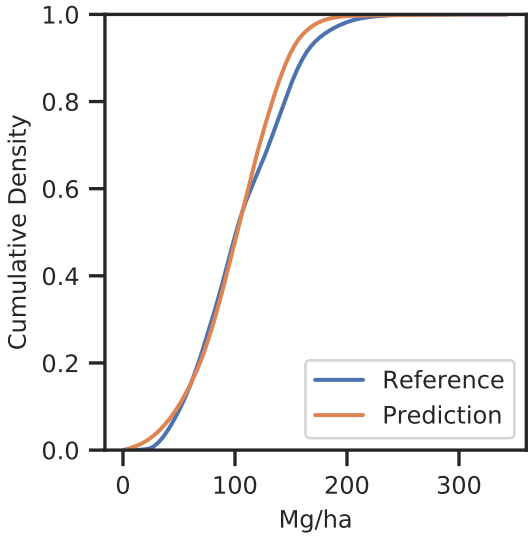


(a) Zero excluded

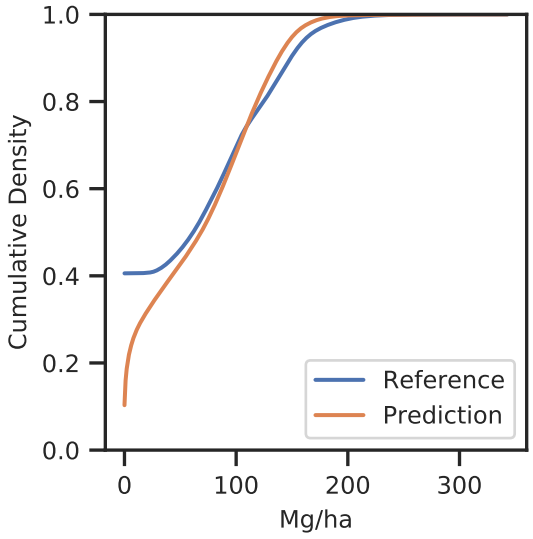


(b) Zero included

Ordinary frequency histogram (zone 58)



(a) Zero excluded

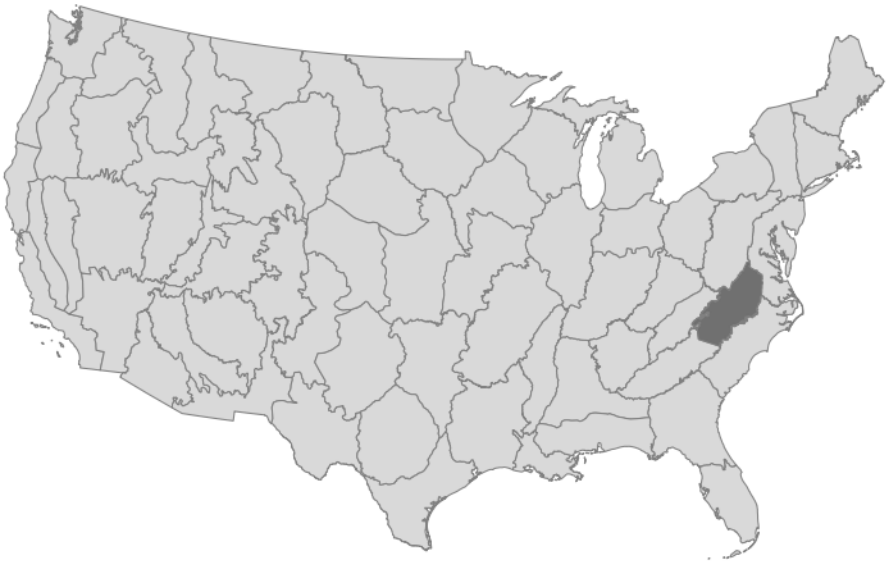


(b) Zero included

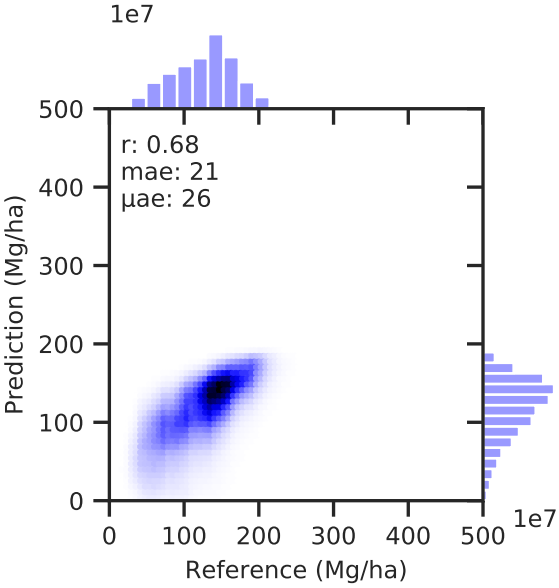
Cumulative density histogram (zone 58)

Return to zone table

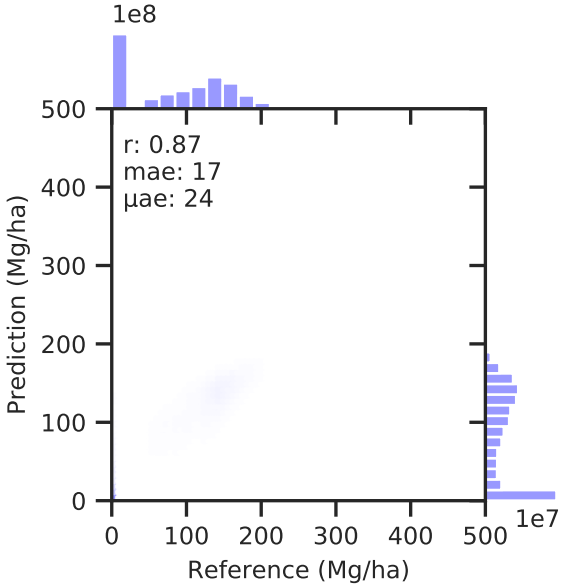
Zone 59



Zone map (zone 59)

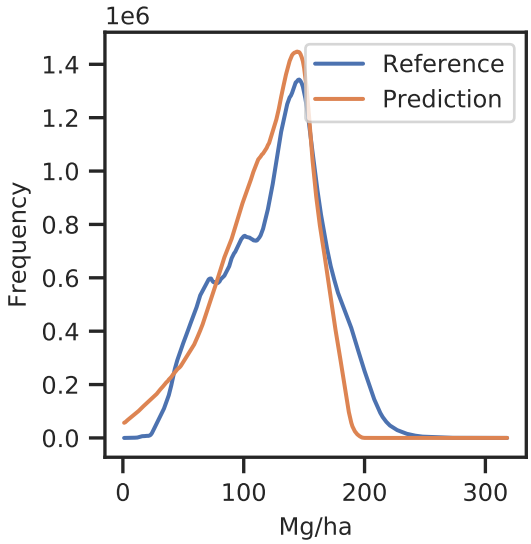


(a) Zero excluded

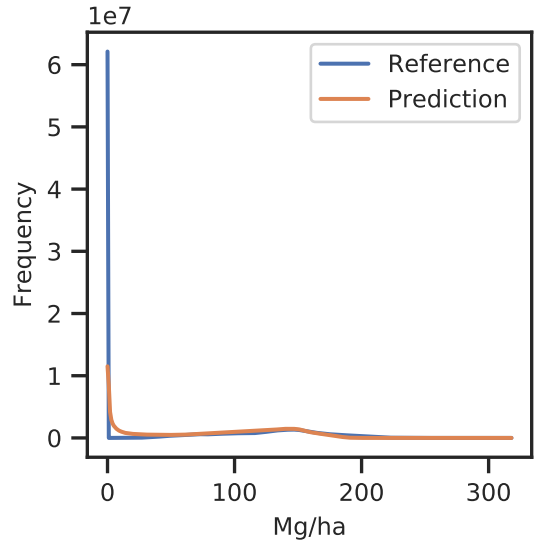


(b) Zero included

2-D frequency histogram (zone 59)

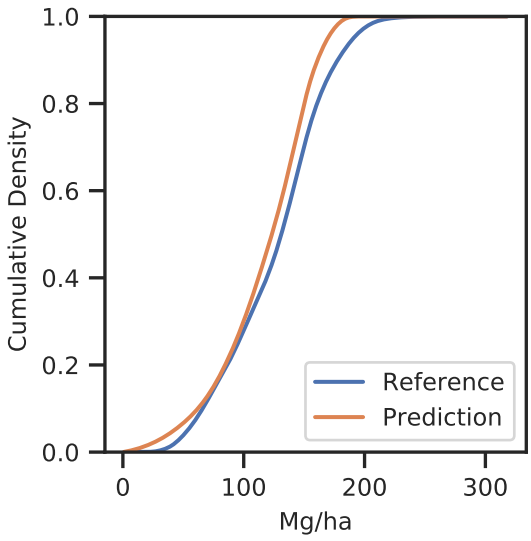


(a) Zero excluded

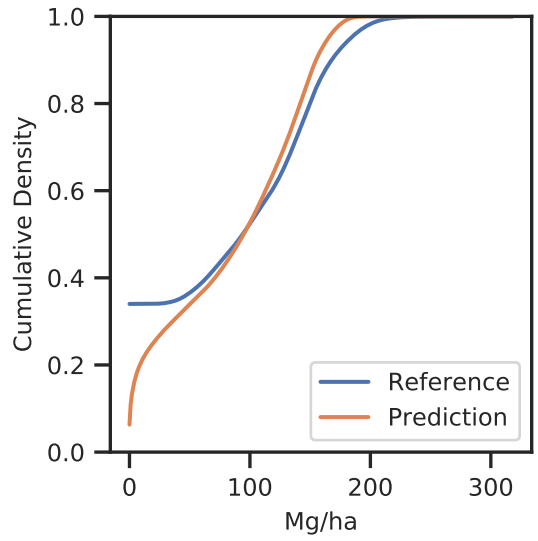


(b) Zero included

Ordinary frequency histogram (zone 59)



(a) Zero excluded



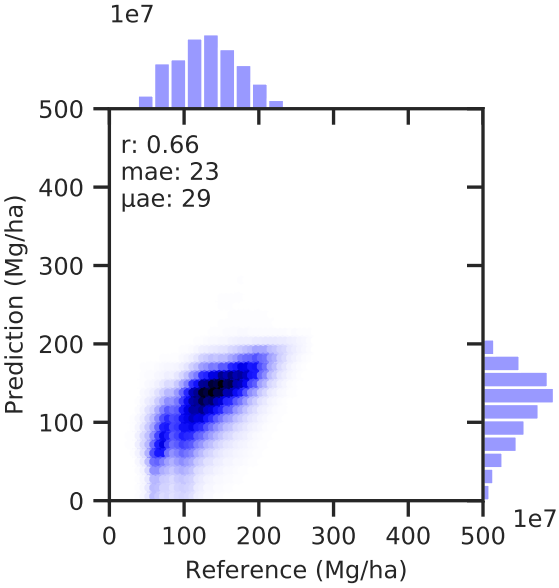
(b) Zero included

Cumulative density histogram (zone 59)

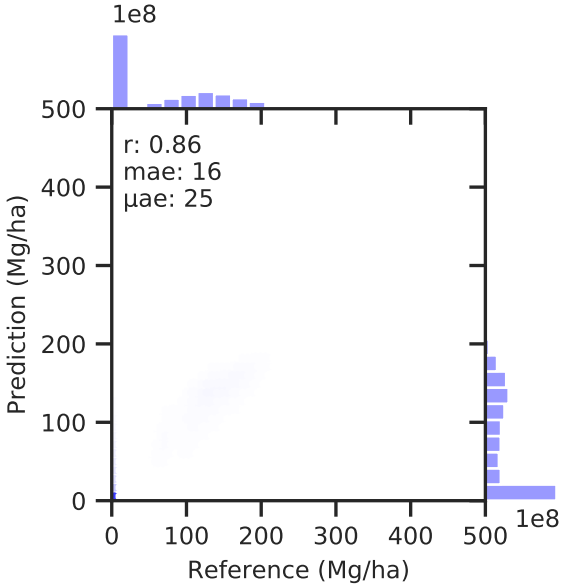
Return to zone table

Zone 60

Zone map (zone 60)

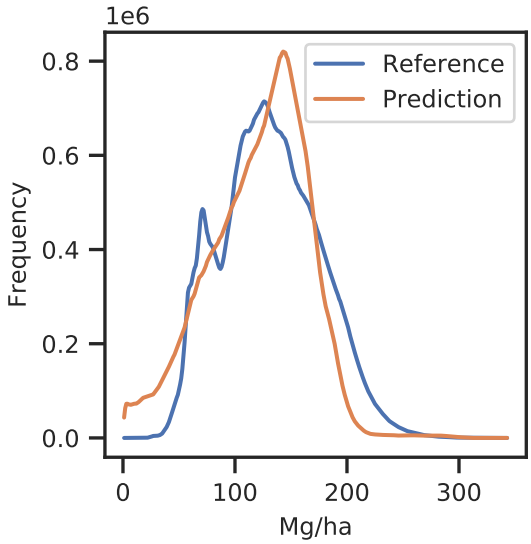


(a) Zero excluded

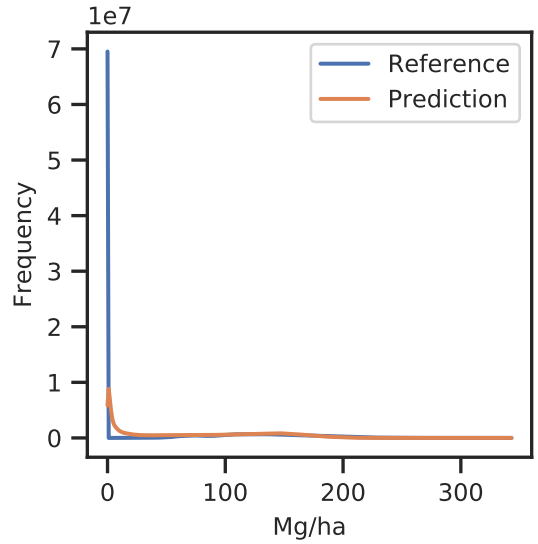


(b) Zero included

2-D frequency histogram (zone 60)

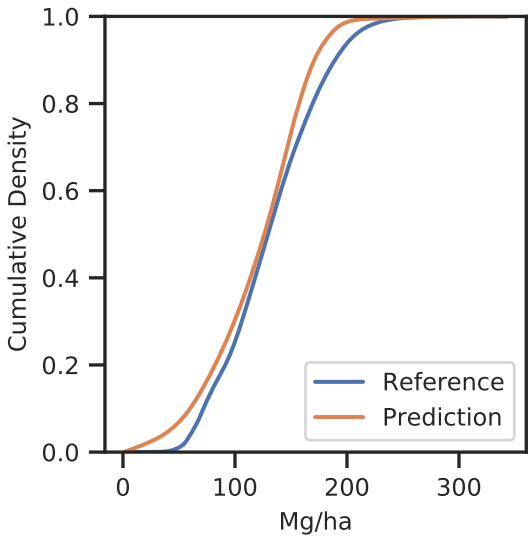


(a) Zero excluded

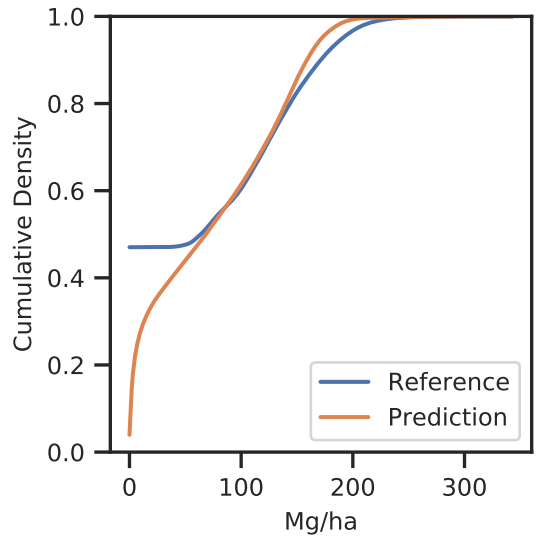


(b) Zero included

Ordinary frequency histogram (zone 60)



(a) Zero excluded

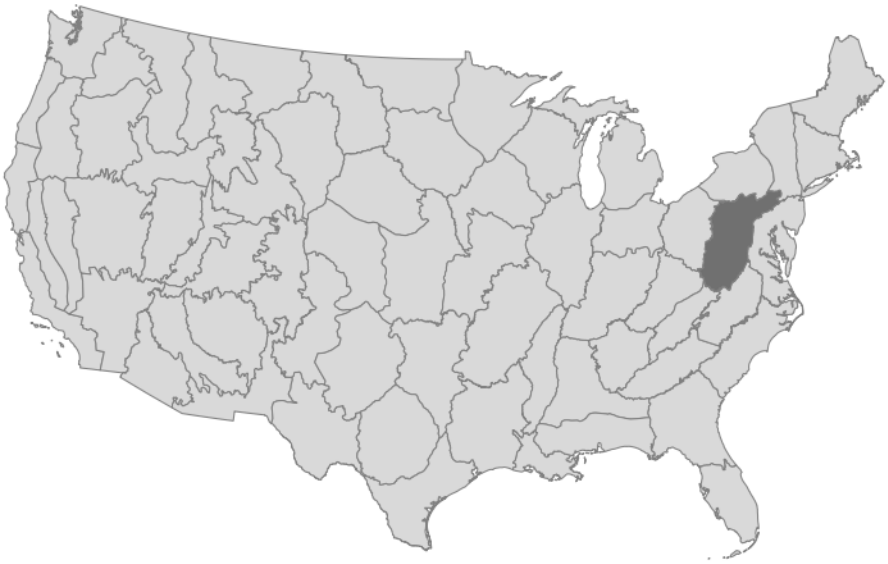


(b) Zero included

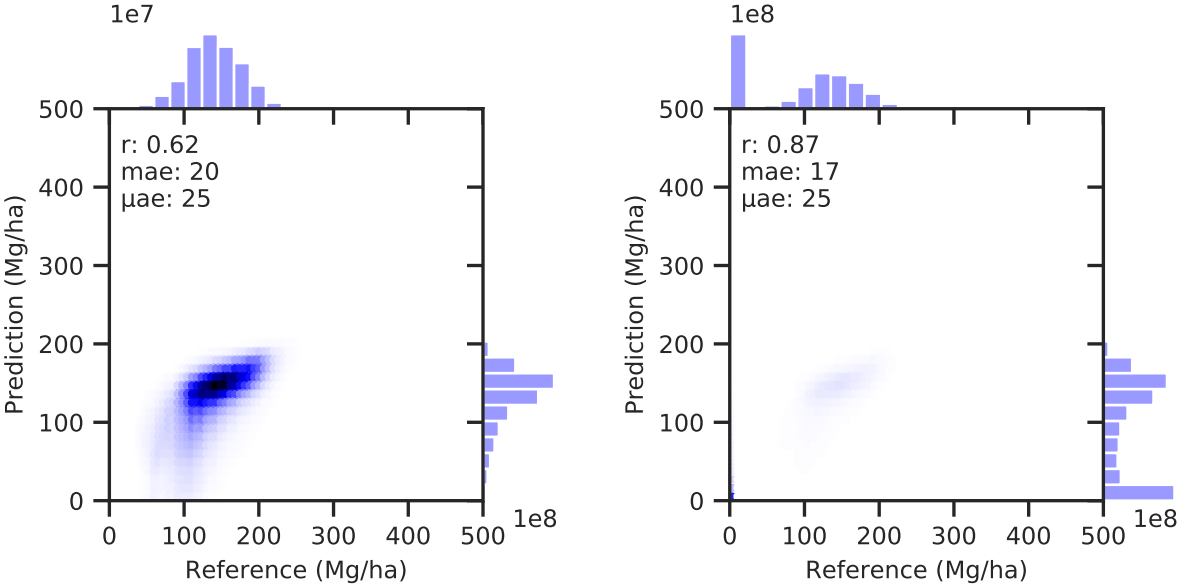
Cumulative density histogram (zone 60)

Return to zone table

Zone 61



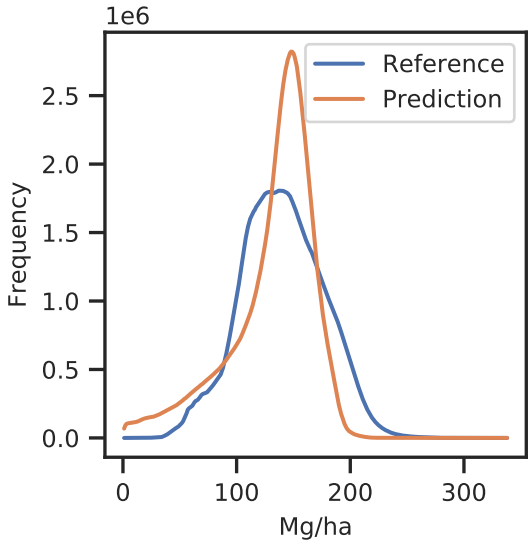
Zone map (zone 61)



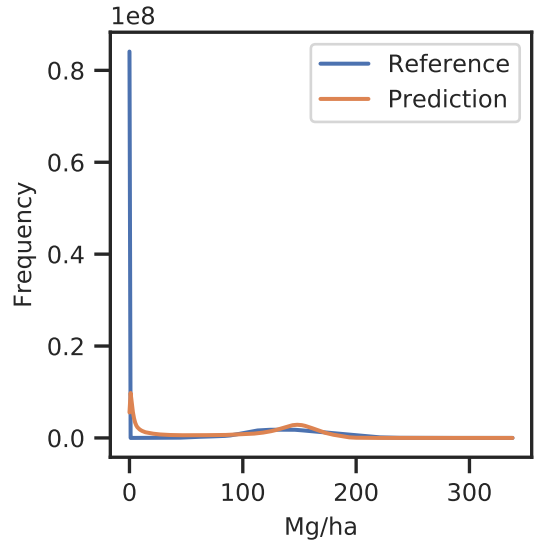
(a) Zero excluded

(b) Zero included

2-D frequency histogram (zone 61)

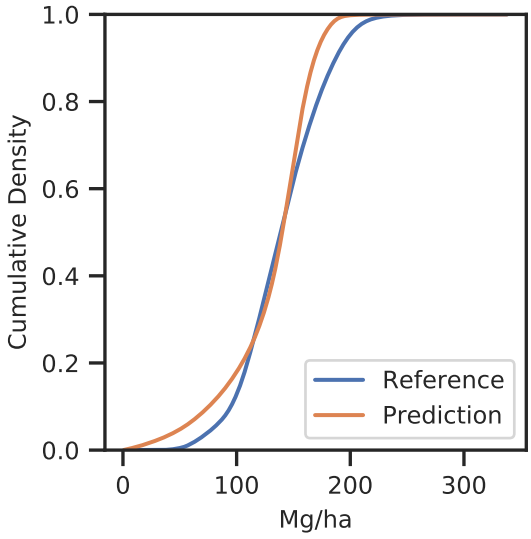


(a) Zero excluded

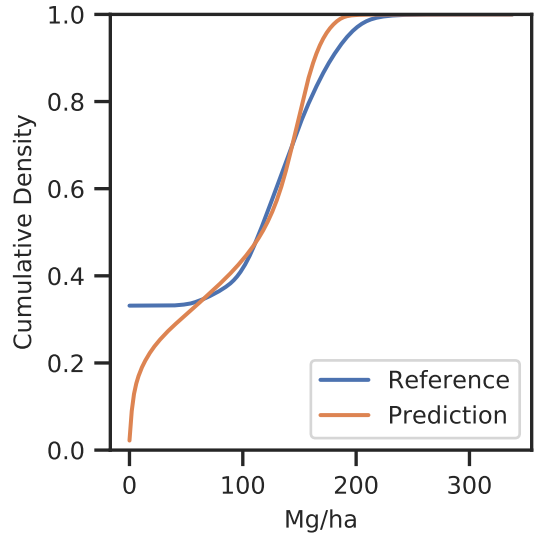


(b) Zero included

Ordinary frequency histogram (zone 61)



(a) Zero excluded

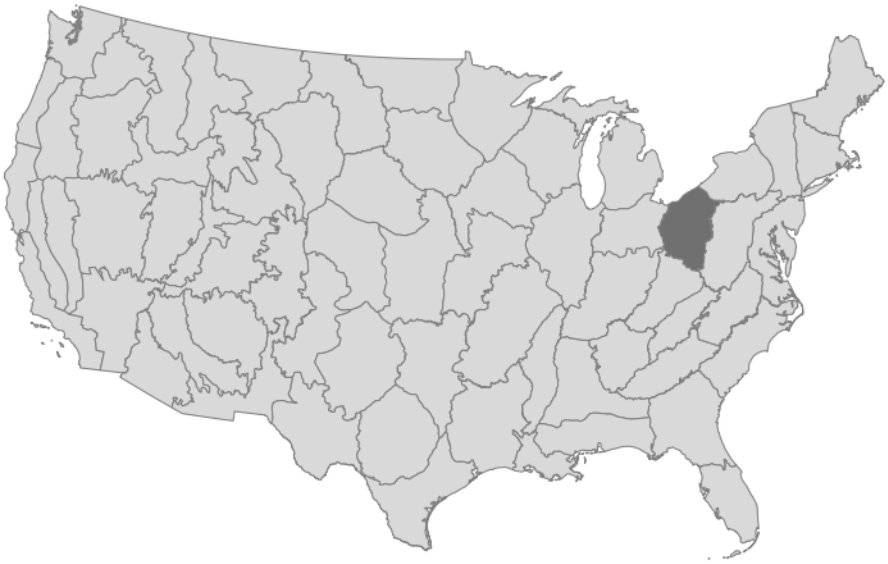


(b) Zero included

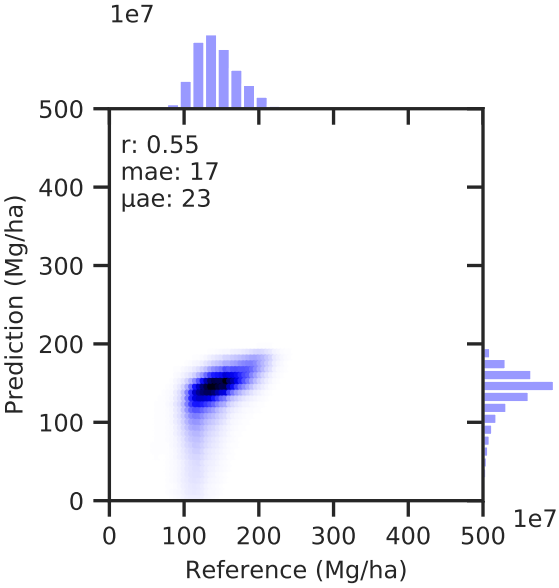
Cumulative density histogram (zone 61)

Return to zone table

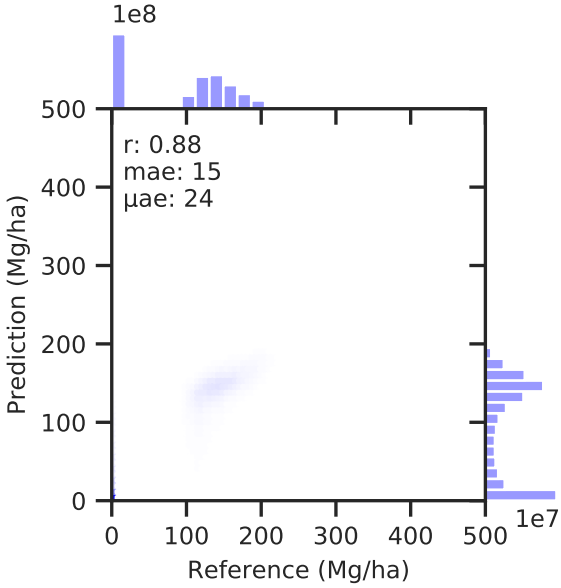
Zone 62



Zone map (zone 62)

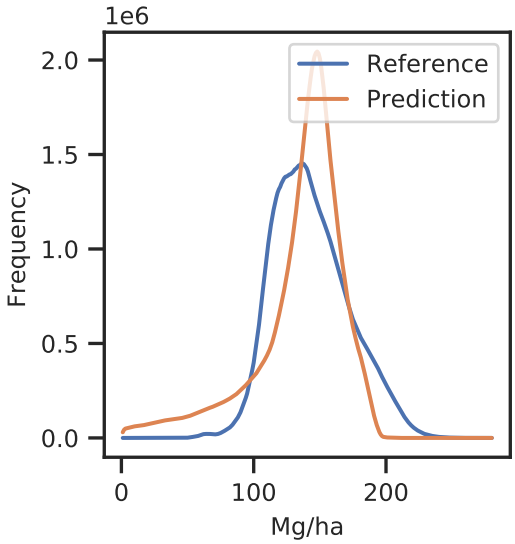


(a) Zero excluded

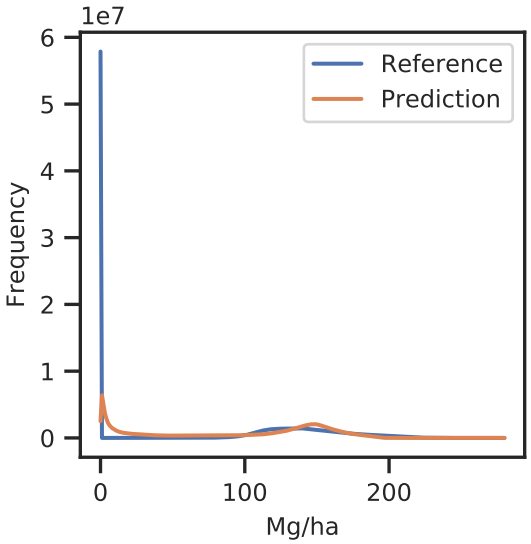


(b) Zero included

2-D frequency histogram (zone 62)

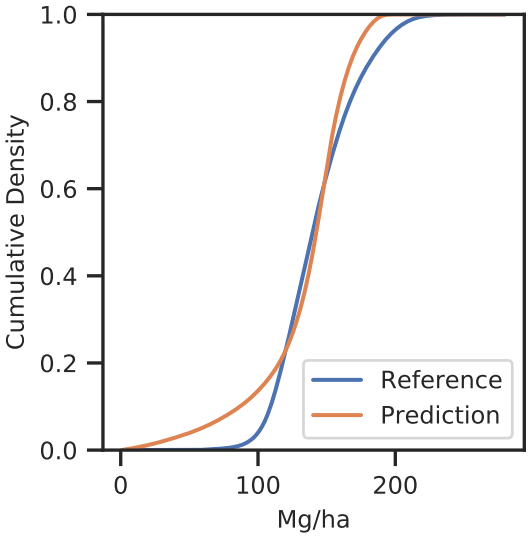


(a) Zero excluded

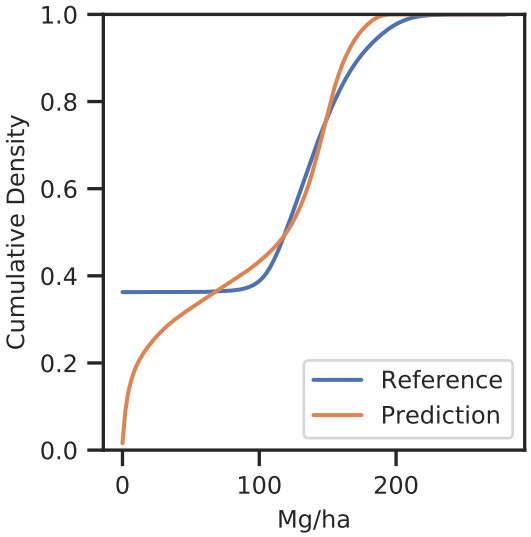


(b) Zero included

Ordinary frequency histogram (zone 62)



(a) Zero excluded



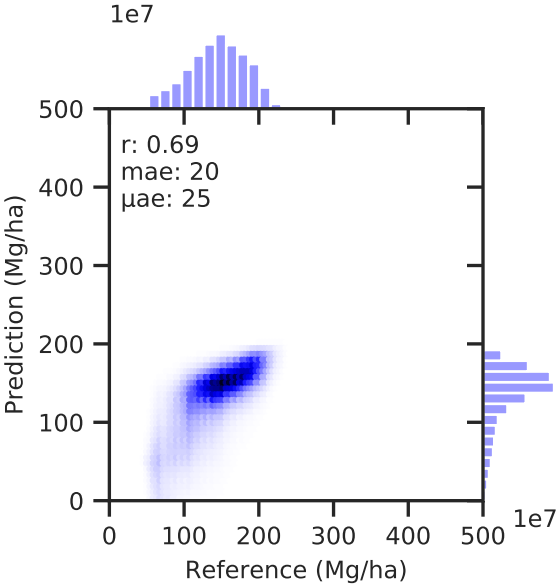
(b) Zero included

Cumulative density histogram (zone 62)

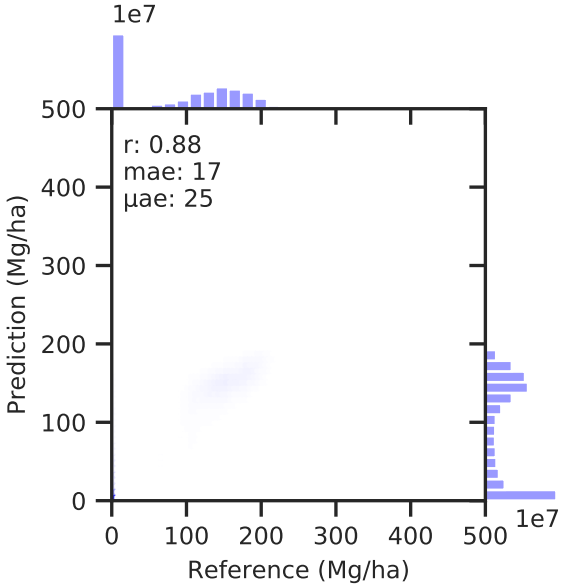
Return to zone table

Zone 63

Zone map (zone 63)

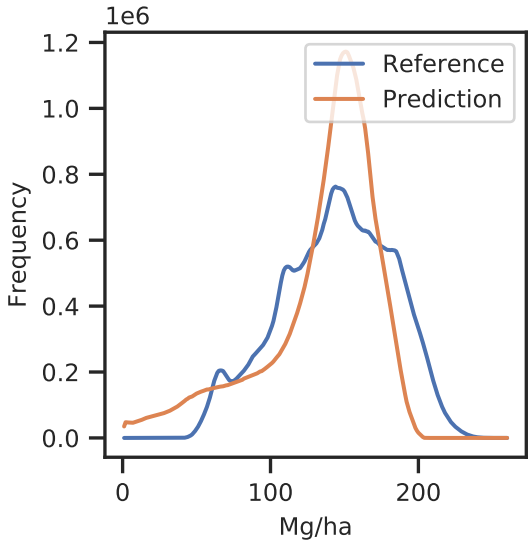


(a) Zero excluded

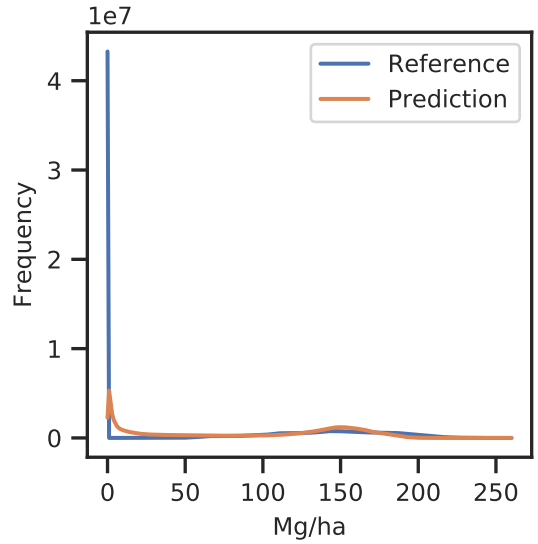


(b) Zero included

2-D frequency histogram (zone 63)

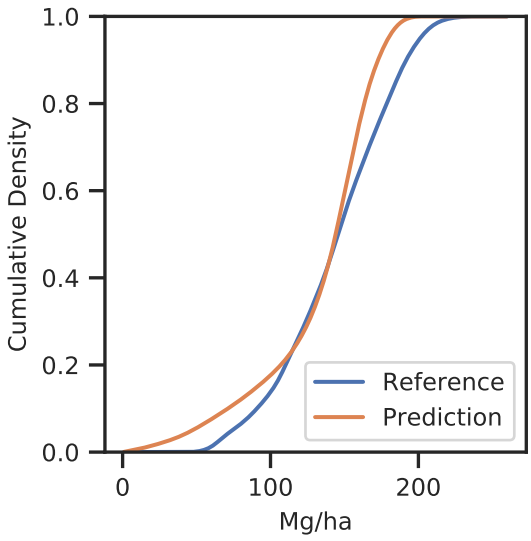


(a) Zero excluded

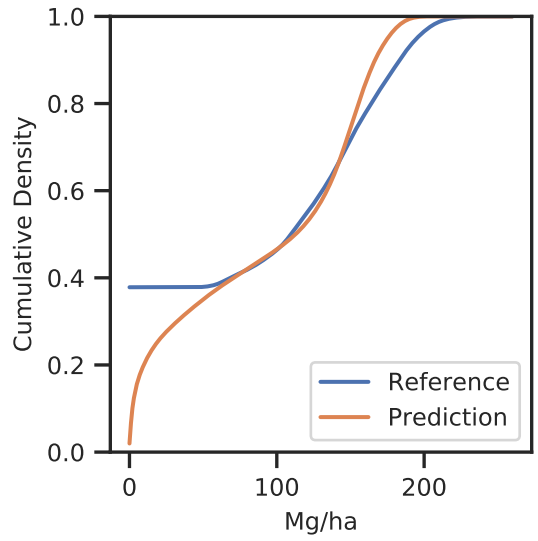


(b) Zero included

Ordinary frequency histogram (zone 63)



(a) Zero excluded



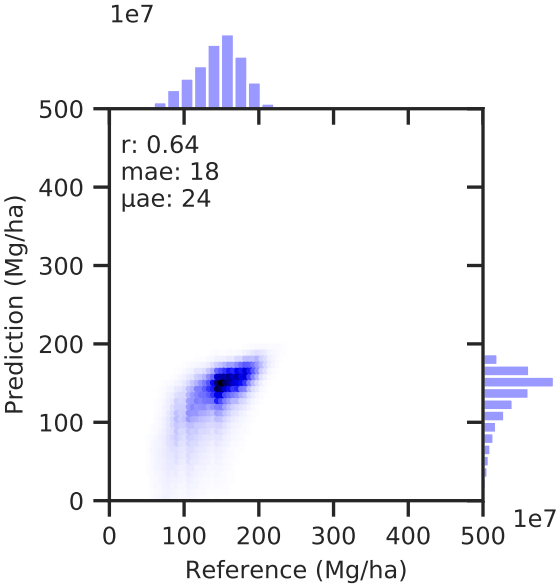
(b) Zero included

Cumulative density histogram (zone 63)

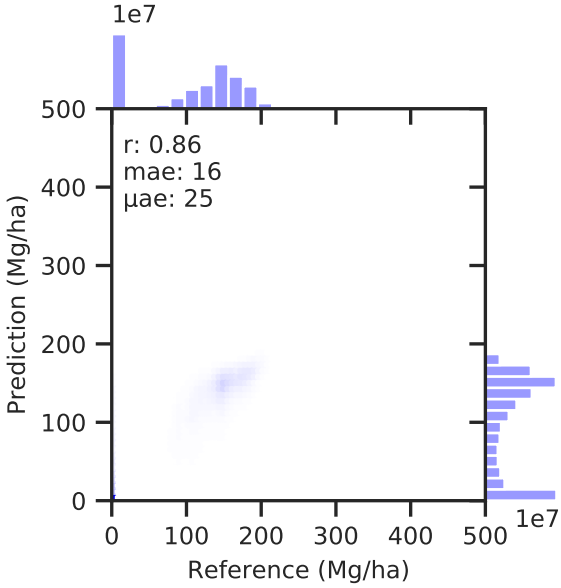
Return to zone table

Zone 64

Zone map (zone 64)

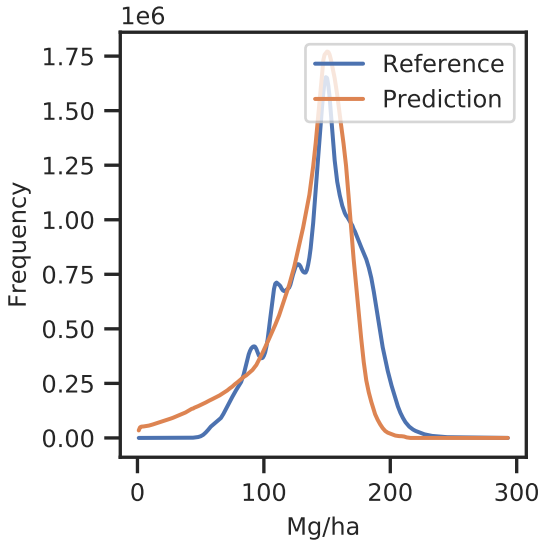


(a) Zero excluded

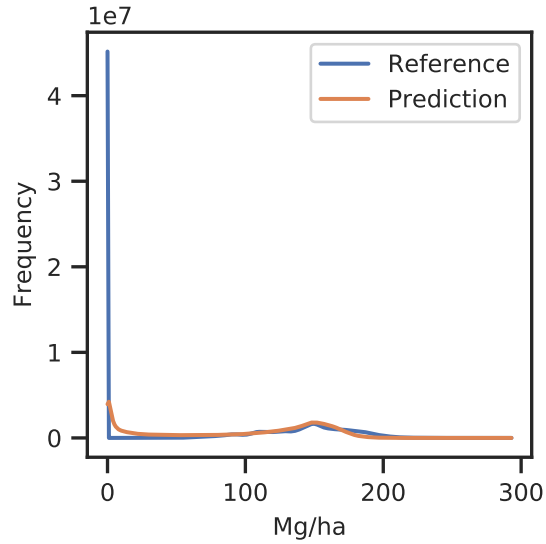


(b) Zero included

2-D frequency histogram (zone 64)

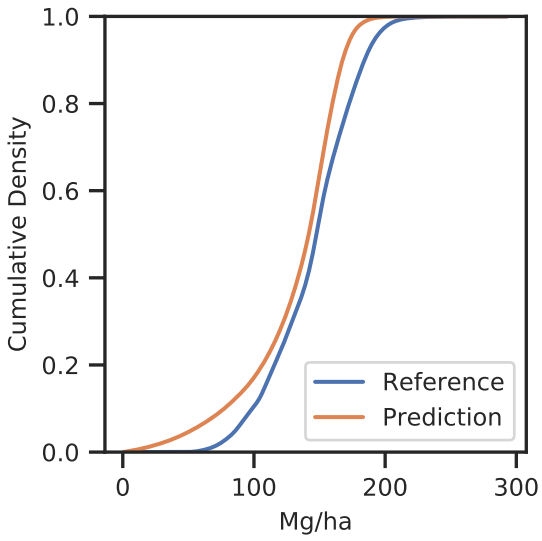


(a) Zero excluded

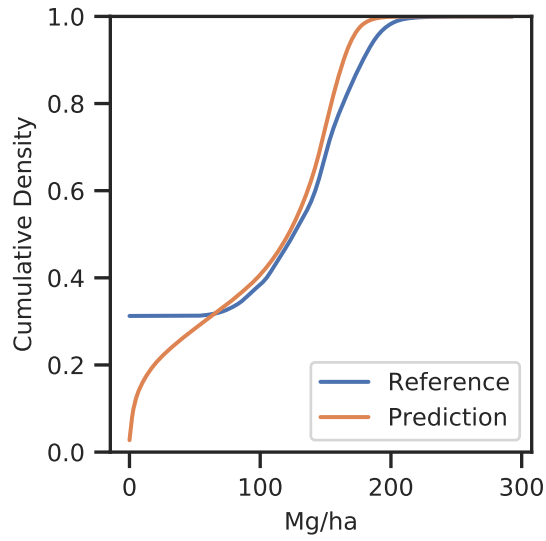


(b) Zero included

Ordinary frequency histogram (zone 64)



(a) Zero excluded



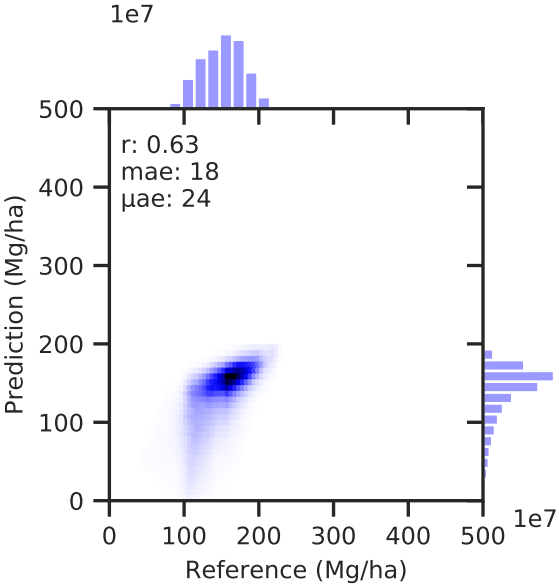
(b) Zero included

Cumulative density histogram (zone 64)

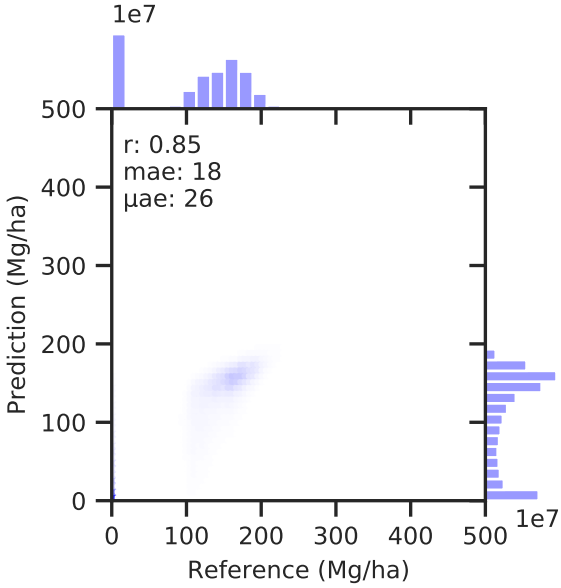
Return to zone table

Zone 65

Zone map (zone 65)

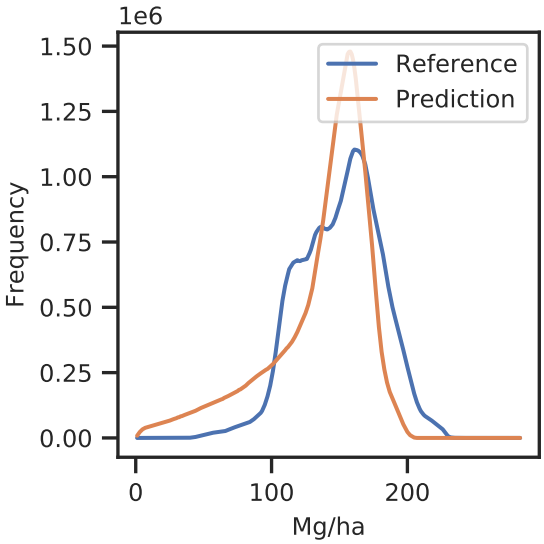


(a) Zero excluded

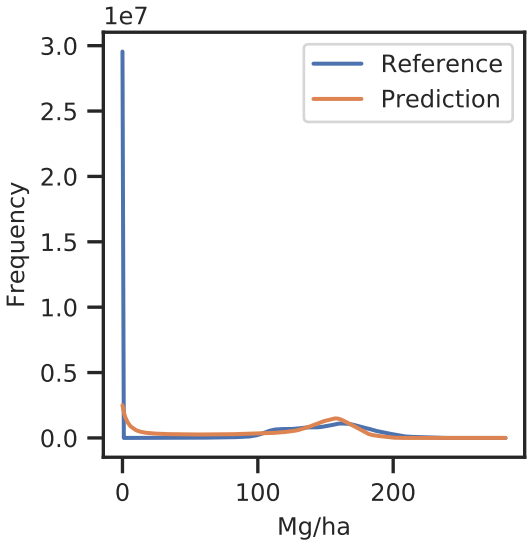


(b) Zero included

2-D frequency histogram (zone 65)

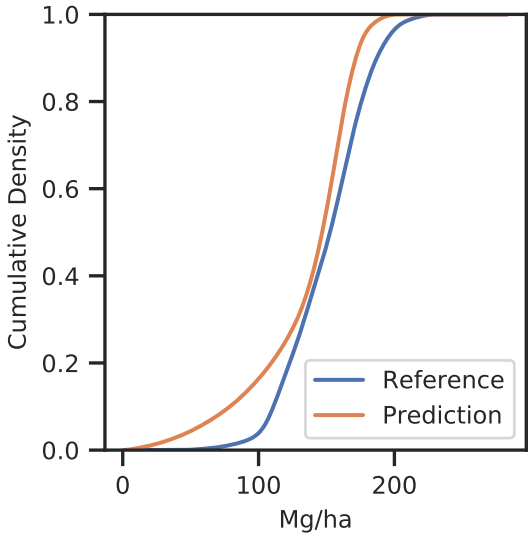


(a) Zero excluded

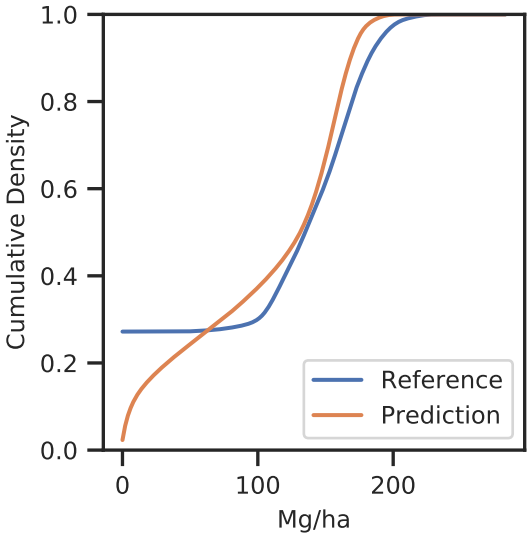


(b) Zero included

Ordinary frequency histogram (zone 65)



(a) Zero excluded



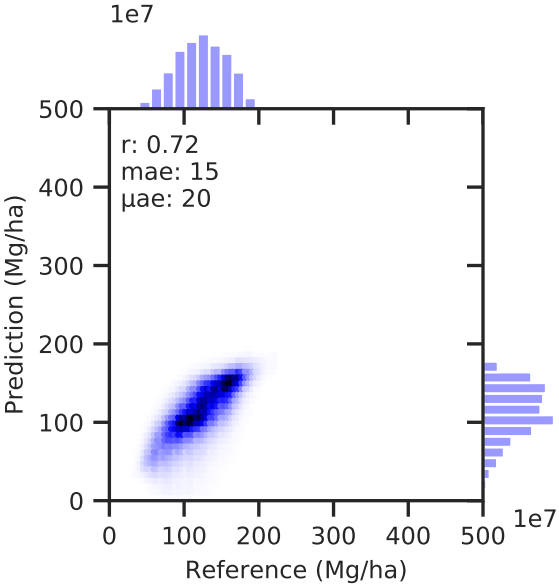
(b) Zero included

Cumulative density histogram (zone 65)

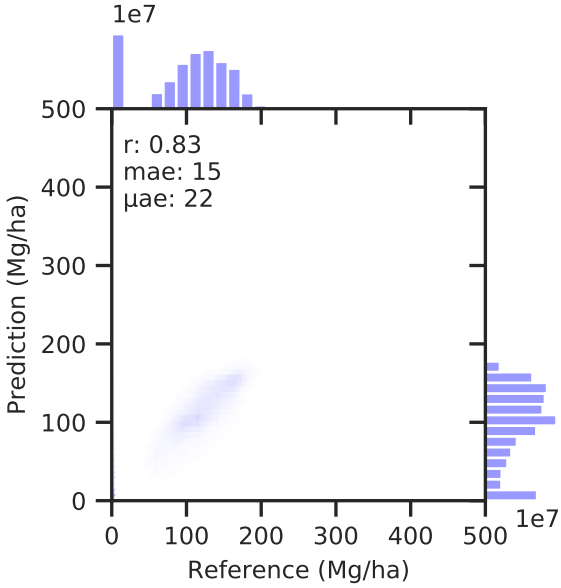
Return to zone table

Zone 66

Zone map (zone 66)

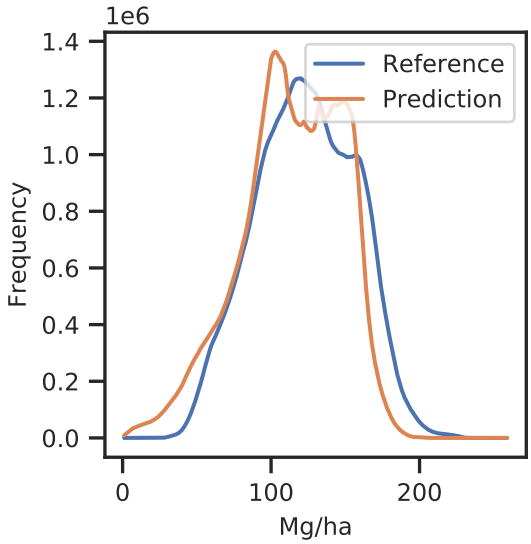


(a) Zero excluded

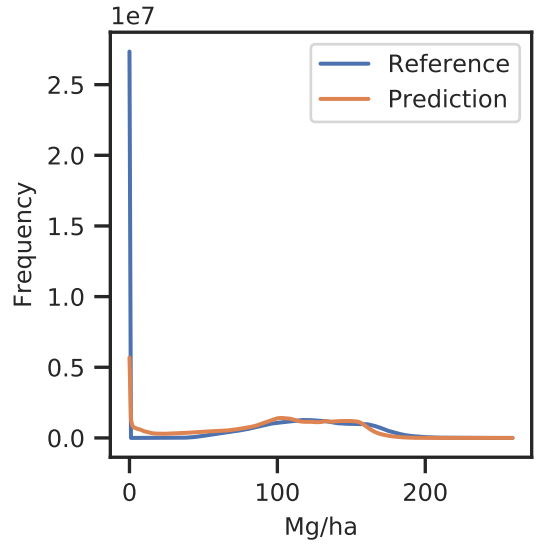


(b) Zero included

2-D frequency histogram (zone 66)

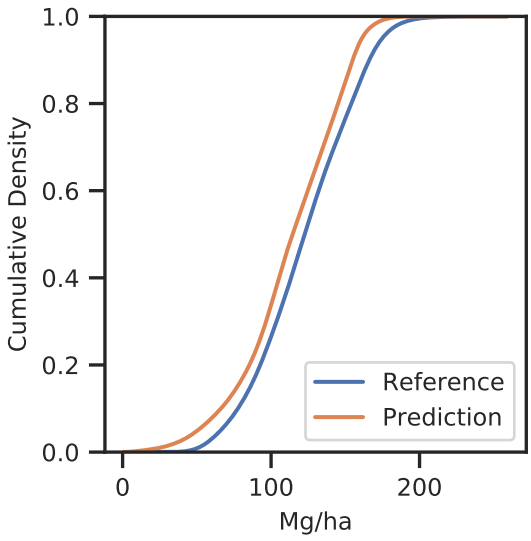


(a) Zero excluded

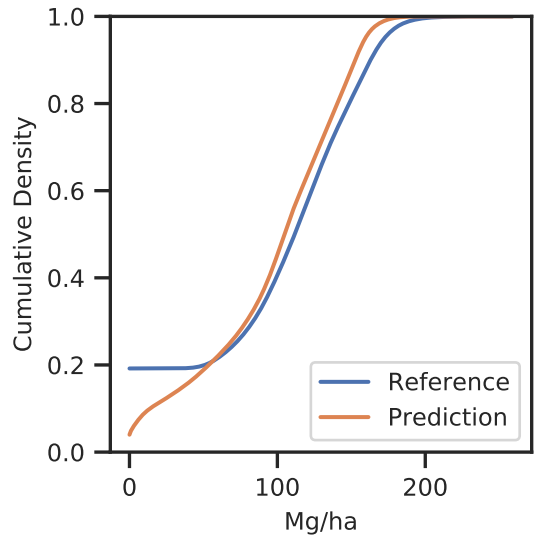


(b) Zero included

Ordinary frequency histogram (zone 66)



(a) Zero excluded



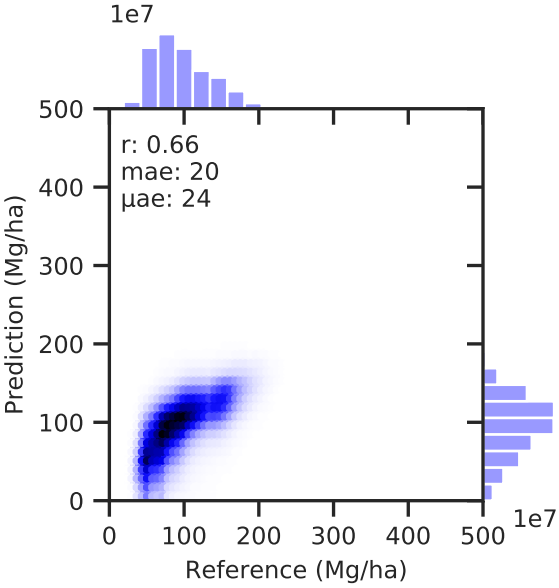
(b) Zero included

Cumulative density histogram (zone 66)

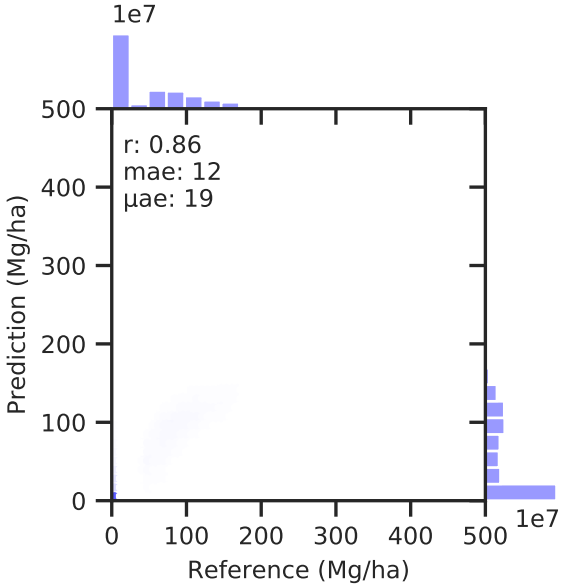
Return to zone table

Zone 98

Zone map (zone 98)

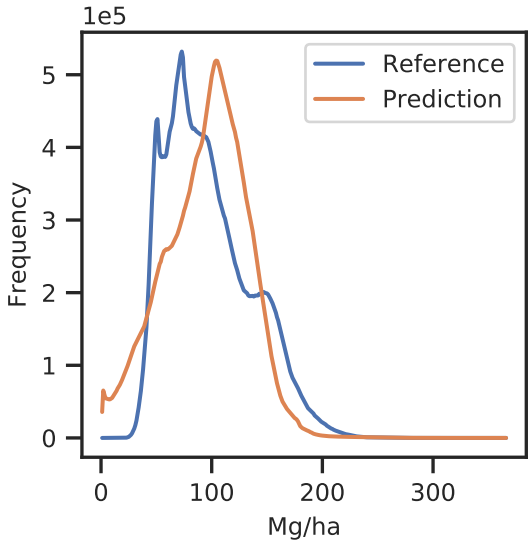


(a) Zero excluded

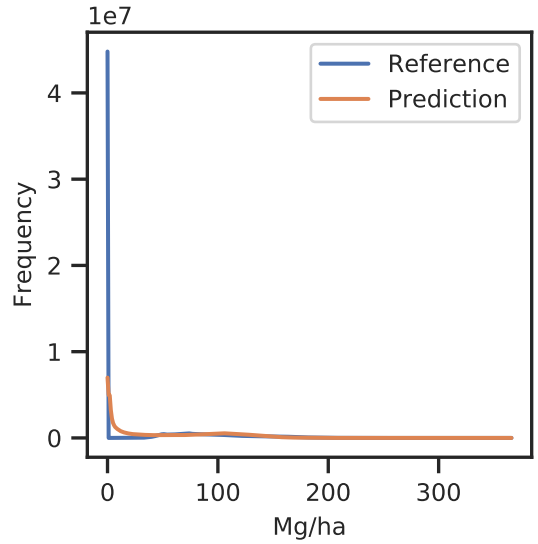


(b) Zero included

2-D frequency histogram (zone 98)

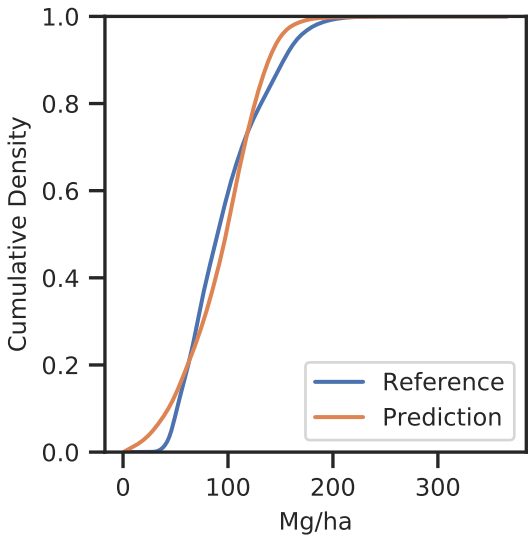


(a) Zero excluded

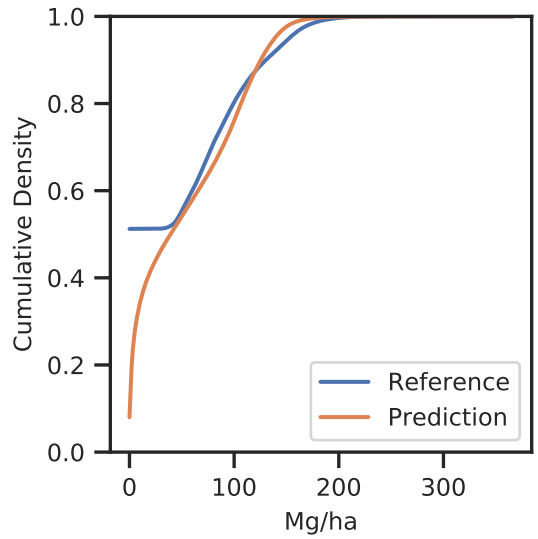


(b) Zero included

Ordinary frequency histogram (zone 98)



(a) Zero excluded



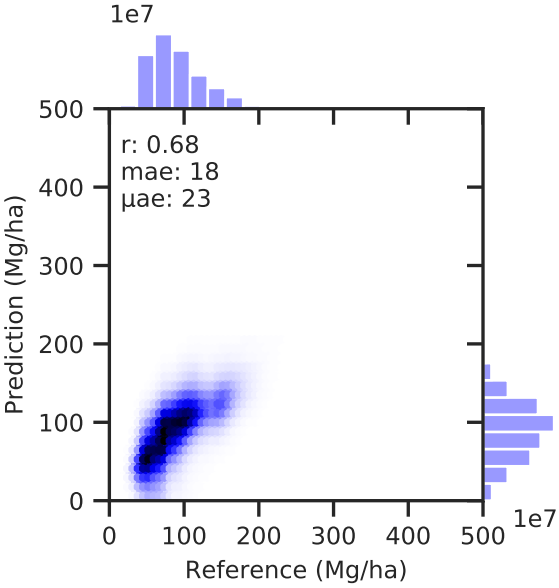
(b) Zero included

Cumulative density histogram (zone 98)

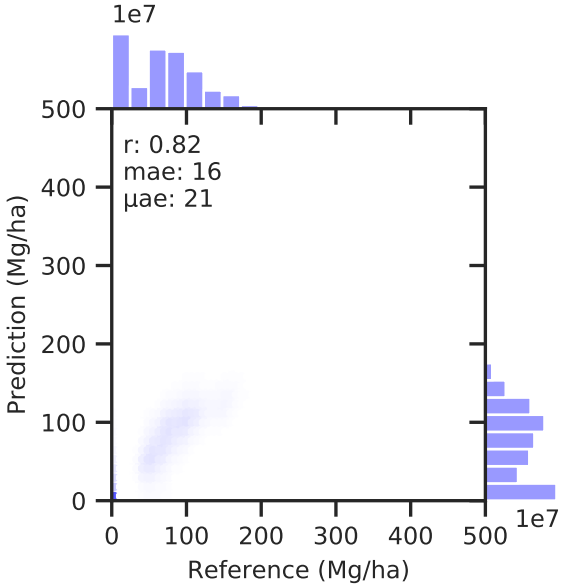
Return to zone table

Zone 99

Zone map (zone 99)

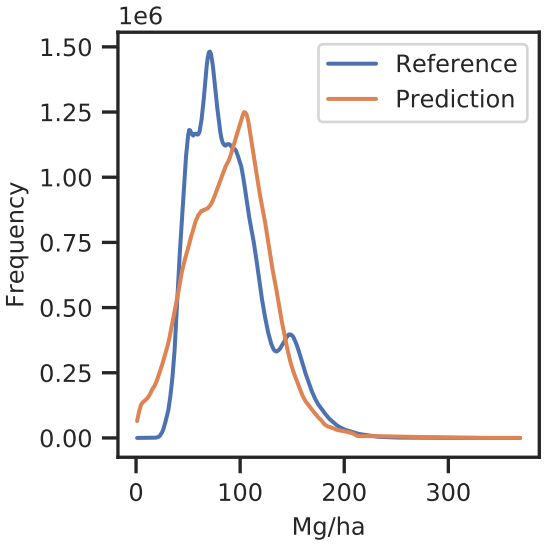


(a) Zero excluded

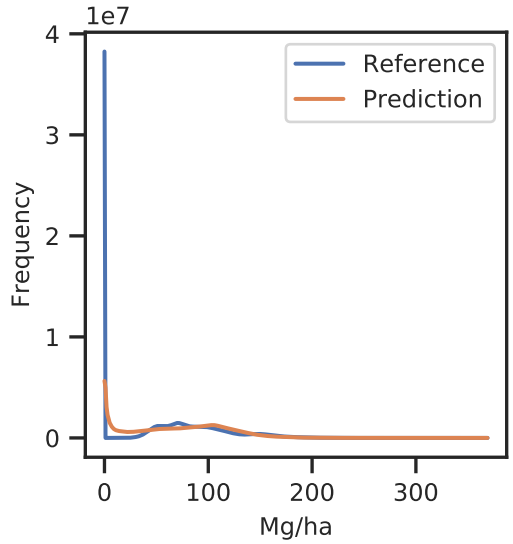


(b) Zero included

2-D frequency histogram (zone 99)

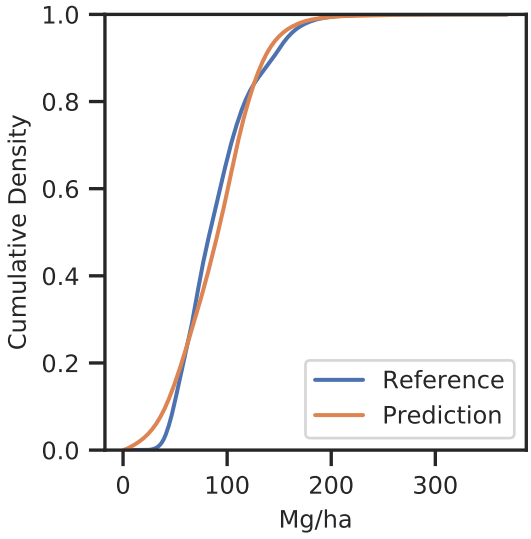


(a) Zero excluded

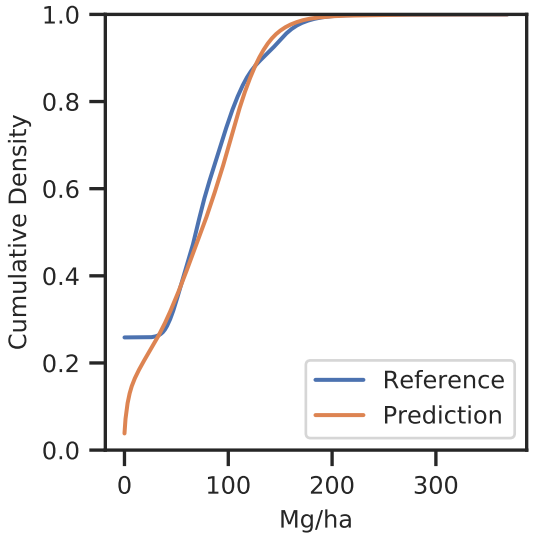


(b) Zero included

Ordinary frequency histogram (zone 99)



(a) Zero excluded



(b) Zero included

Cumulative density histogram (zone 99)

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References

Crist, E. P. (1985). A tm tasseled cap equivalent transformation for reflectance factor data. *Remote Sensing of Environment*, 17(3):301–306.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. (2017). Google earth engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202:18–27.

Hall, D. K., Riggs, G. A., and Salomonson, V. V. (1995). Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data. *Remote sensing of Environment*, 54(2):127–140.

Homer, C. and Gallant, A. (2001). Partitioning the conterminous united states into mapping zones for landsat tm land cover mapping. *Unpublished US Geologic Survey report. http://landcover. usgs. gov/pdf/homer. pdf.(1 August 2008).*

Homer, C., Huang, C., Yang, L., Wylie, B., and Coan, M. (2004). Development of a 2001 national land-cover database for the united states. *Photogrammetric Engineering & Remote Sensing*, 70(7):829–840.

Hooper, S. and Kennedy, R. E. (2018). A spatial ensemble approach for broad-area mapping of land surface properties. *Remote Sensing of Environment*, 210:473–489.

Kellndorfer, J., Walker, W., Kirsch, K., Fiske, G., Bishop, J., LaPoint, L., Hoppus, M., and Westfall, J. (2013). Nacp aboveground biomass and carbon baseline data, v. 2 (nbcd 2000), usa, 2000. *ORNL DAAC*.

Kennedy, R. E., Ohmann, J., Gregory, M., Roberts, H., Yang, Z., Bell, D. M., Kane, V., Hughes, M. J., Cohen, W. B., Powell, S., et al. (2018a). An empirical, integrated forest biomass monitoring system. *Environmental Research Letters*, 13(2):025004.

Kennedy, R. E., Yang, Z., and Cohen, W. B. (2010). Detecting trends in forest disturbance and recovery using yearly landsat time series: 1. landtrendr—temporal segmentation algorithms. *Remote Sensing of Environment*, 114(12):2897–2910.

Kennedy, R. E., Yang, Z., Gorelick, N., Braaten, J., Cavalcante, L., Cohen, W. B., and Healey, S. (2018b). Implementation of the landtrendr algorithm on google earth engine. *Remote Sensing*, 10(5).

Key, C. and Benson, N. (2005). Landscape assessment: remote sensing of severity, the normalized burn ratio and ground measure of severity, the composite burn index. *FIREMON: Fire effects monitoring and inventory system Ogden, Utah: USDA Forest Service, Rocky Mountain Res. Station*.

Masek, J. G., Vermote, E. F., Saleous, N. E., Wolfe, R., Hall, F. G., Huemmrich, K. F., Gao, F., Kutler, J., and Lim, T.-K. (2006). A landsat surface reflectance dataset for north america, 1990-2000. *IEEE Geoscience and Remote Sensing Letters*, 3(1):68–72.

Omernik, J. M. and Griffith, G. E. (2014). Ecoregions of the conterminous united states: evolution of a hierarchical spatial framework. *Environmental management*, 54(6):1249–1266.

Rouse Jr, J., Haas, R., Schell, J., and Deering, D. (1974). Monitoring vegetation systems in the great plains with erts.

Roy, D. P., Kovalskyy, V., Zhang, H., Vermote, E. F., Yan, L., Kumar, S., and Egorov, A. (2016). Characterization of landsat-7 to landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sensing of Environment*, 185:57–70.

Vermote, E., Justice, C., Claverie, M., and Franch, B. (2016). Preliminary analysis of the performance of the landsat 8/oli land surface reflectance product. *Remote Sensing of Environment*, 185:46–56.

Vogeler, J. C., Braaten, J. D., Slesak, R. A., and Falkowski, M. J. (2018). Extracting the full value of the landsat archive: Inter-sensor harmonization for the mapping of minnesota forest canopy cover (1973–2015). *Remote Sensing of Environment*, 209:363–374.

Weiss, A. (2001). Topographic position and landforms analysis. In *Poster presentation, ESRI user conference, San Diego, CA*, volume 200.

Zhu, Z., Wang, S., and Woodcock, C. E. (2015). Improvement and expansion of the fmask algorithm: Cloud, cloud shadow, and snow detection for landsats 4–7, 8, and sentinel 2 images. *Remote Sensing of Environment*, 159:269–277.