

Supplementary Materials



## A Decision Tree Approach for Spatially Interpolating Missing Land Cover Data and Classifying Satellite Images

## Jacinta Holloway 1,\*, Kate J. Helmstedt 1, Kerrie Mengersen 1 and Michael Schmidt 2

- <sup>1</sup> ARC Centre of Excellence for Mathematical and Statistical Frontiers (ACEMS), Queensland University of Technology, Brisbane 4001, Australia
- <sup>2</sup> German Aerospace Centre (DLR), 51147 Cologne, Germany
- \* Correspondence: j1.holloway@qut.edu.au

Received: 21 May 2019; Accepted: 29 July 2019; Published: 31 July 2019

**Table S1.** Random forest binary classification results by image date, by cloud pattern and pixel class for each date. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image	Cloud	Pixel	Sample	Overall	Lower	Upper	Producer's	User's
date	pattern	class	number	accuracy	CI	CI	accuracy	accuracy
	Small	Missing	1	0.768	0.749	0.786	0.704	0.882
	Small	Observed	1	0.766	0.747	0.784	0.628	0.846
	Large	Observed	1	0.842	0.837	0.847	0.887	0.757
date 16/7/00 2/9/00	Large	Missing	1	0.813	0.796	0.830	0.643	0.726
	Small	Observed	2	0.766	0.747	0.785	0.631	0.833
	Small	Missing	2	0.762	0.742	0.780	0.558	0.847
	Large	Observed	2	0.783	0.765	0.801	0.642	0.855
	Large	Missing	2	0.685	0.664	0.705	0.531	0.765
	Small	Missing	1	0.814	0.796	0.831	0.637	0.811
	Small	Observed	1	0.773	0.754	0.792	0.625	0.853
	Large	Observed	1	0.771	0.752	0.789	0.648	0.835
2/0/00	Large	Missing	1	0.739	0.719	0.758	0.599	0.804
2/9/00	Small	Missing	2	0.820	0.802	0.836	0.671	0.818
	Small	Observed	2	0.786	0.767	0.803	0.682	0.844
	Large	Observed	2	0.785	0.766	0.803	0.660	0.856
	Large	Missing	2	0.719	0.699	0.739	0.614	0.807
	Small	Missing	1	0.903	0.889	0.915	0.906	0.761
	Small	Observed	1	0.835	0.818	0.851	0.905	0.689
	Large	Missing	1	0.891	0.877	0.905	0.935	0.389
19/0/00	Large	Observed	1	0.855	0.839	0.871	0.903	0.769
10/9/00	Small	Observed	2	0.844	0.827	0.859	0.907	0.717
	Small	Missing	2	0.835	0.818	0.851	0.876	0.765
	Large	Observed	2	0.861	0.845	0.876	0.914	0.769
	Large	Missing	2	0.836	0.820	0.852	0.928	0.498

Random forest had an overall accuracy range from 0.69 to 0.90 across all images and missing and observed pixels. Random forest had the highest accuracy (the top 5 results). The highest accuracy results for random forest were for the missing pixels in the small clouds and large clouds in the 18 September 2000 image, followed by observed pixels in the same image. The lowest accuracy results for random forest for binary FPC classification were for the 16 July 2000 and 2 September 2000 images for the missing pixels, which have more balanced class groups. The lowest accuracy result for this was 0.69 for the missing pixels in the large clouds in July and missing pixels in the large clouds in the 2 September 2000 image.

**Table S2.** Gradient boosted machine binary classification results by image date, by cloud pattern and pixel class for each date. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image	Cloud	Pixel	Sample	Overall	Lower	Upper	Producer's	User's
date	pattern	class	number	accuracy	CI	CI	accuracy	accuracy
	Small	Missing	1	0.705	0.685	0.725	0.245	0.918
	Small	Observed	1	0.683	0.662	0.703	0.292	0.904
	Small	Missing	2	0.728	0.708	0.747	0.227	0.950
16/7/00	Small	Observed	2	0.681	0.660	0.701	0.367	0.891
	Large	Missing	1	0.724	0.704	0.744	0.292	0.904
	Large	Observed	1	0.720	0.714	0.726	0.330	0.923
	Large	Observed	2	0.714	0.694	0.734	0.313	0.843
	Large	Missing	2	0.626	0.604	0.647	0.291	0.908
	Small	Observed	1	0.707	0.686	0.727	0.416	0.878
	Small	Missing	1	0.688	0.667	0.708	0.401	0.899
	Small	Missing	2	0.708	0.688	0.728	0.466	0.855
2/0/00	Small	Observed	2	0.707	0.687	0.727	0.377	0.883
2/9/00	Large	Missing	1	0.702	0.681	0.722	0.450	0.814
	Large	Observed	1	0.701	0.681	0.721	0.461	0.825
	Large	Observed	2	0.720	0.700	0.740	0.382	0.855
	Large	Missing	2	0.693	0.673	0.714	0.346	0.892
	Small	Missing	1	0.819	0.802	0.836	0.979	0.132
	Small	Observed	1	0.793	0.775	0.811	0.882	0.685
	Small	Missing	2	0.826	0.809	0.842	0.878	0.726
10/0/00	Small	Observed	2	0.799	0.781	0.816	0.919	0.559
18/9/00	Large	Observed	1	0.814	0.797	0.831	0.969	0.214
	Large	Missing	1	0.783	0.765	0.801	0.8675	0.756
	Large	Observed	2	0.810	0.793	0.827	0.915	0.536
	Large	Missing	2	0.795	0.777	0.812	0.903	0.652

Gradient boosted machine had an overall accuracy range from 0.63 to 0.83 across all images and missing and observed pixels. Gradient boosted machine had the highest accuracy for missing pixels in the 18 September 2000 image for both the large and small cloud patterns, and for both samples of the small cloud pattern image. Other high accuracy results for this method were also for the observed pixels in the 18 September image, and missing pixels in the large cloud pattern for this image. The lowest accuracy result was the 16 July image for missing pixels in the large cloud pattern, followed by observed pixels in the small cloud pattern for the same image.

**Table S3.** Binary FPC Anova results. Tukey posthoc comparison results showing differences in mean overall accuracy between image dates.

Image date comparisons	Difference	p value
18/9/2000-16/7/2000	0.0936	<.000
2/9/2000-16/7/2000	-0.00190	0.9927
2/9/2000-18/9/2000	-0.0954	<.000

**Table S4.** Binary FPC Anova results. Tukey posthoc comparison results showing differences in mean overall accuracy between image dates.

Method comparisons	Difference	p value
RF-GBM	0.065	<.000

Table S5. Two-way ANOVA results for differences in mean overall accuracy for binary FPC.

Variable	F statistic	p value
Methods * Image date	1.2469	0.2978
Pixel class * Cloud pattern	2.1925	0.1458
Pixel class * Image date	0.3572	0.7017
Pixel class * Method	0.0378	0.8467
Cloud pattern * Image date	0.3105	0.7347
Cloud pattern * Method	0.0797	0.7790

**Table S6.** Random forest continuous FPC prediction results ordered by image date, by cloud pattern and pixel class for each date. The RMSE and MAE as percentages of mean FPC for each sample are in brackets. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image	Cloud	Pixel	Sample	DMCE	МАЕ
date	pattern	class	number	KWI5E	MAE
	Small	Missing	1	10.568 (9.39%)	8.099 (7.20%)
	Small	Observed	1	13.523 (12.21%)	9.822 (8.87%)
	Small	Missing	2	13.592 (12.16%)	10.937 (9.79%)
16/7/00	Small	Observed	2	13.738 (12.48%)	9.693 (8.80%)
16/7/00	Large	Observed	1	10.107 (8.96%)	7.328 (6.49%)
	Large	Missing	1	11.015 (10.23%)	8.522 (7.91%)
	Large	Observed	2	11.817(10.53%)	9.129 (8.13%)
	Large	Missing	2	16.726 (15.54%)	13.673 (12.70%)
	Small	Missing	1	11.760 (9.53%)	9.203 (7.46%)
	Small	Observed	1	12.017 (9.74%)	8.491 (6.88%)
	Small	Missing	2	11.198 (9.05%)	8.775 (7.09%)
2/0/00	Small	Observed	2	11.823 (9.42%)	8.553 (6.82%)
2/9/00	Large	Observed	1	10.906 (8.72%)	8.125 (6.50%)
	Large	Missing	1	12.624 (10.14%)	9.883 (7.94%)
	Large	Observed	2	10.928 (8.54%)	7.912 (6.18%)
	Large	Missing	2	12.488 (10.09%)	9.755 (7.88%)
	Small	Missing	1	5.323 (4.31%)	3.938 (3.19%)
	Small	Observed	1	8.463 (6.82%)	5.103 (4.11%)
	Small	Missing	2	4.914 (3.98%)	3.677 (2.98%)
10/0/00	Small	Observed	2	6.754 (5.29%)	4.752 (3.72%)
10/9/00	Large	Missing	1	5.486 (5.10%)	3.993 (3.71%)
	Large	Observed	1	7.251 (5.87%)	4.739 (3.84%)
	Large	Observed	2	6.751 (5.45%)	4.458 (3.60%)
	Large	Missing	2	9.394 (7.56%)	6.988 (5.62%)

When predicting FPC values random forest had an RMSE ranging from 4.91 to 16.73. Random forest had the lowest RMSE values (i.e. was more accurate) consistently for the 18 September 2000 image. The lowest RMSE was for missing pixels in the small cloud pattern across both samples for the 18 September image, followed by missing pixels in the large cloud pattern and observed pixels in the same image. The highest RMSE was for predicting FPC values in the 16 July 2000 image for

missing pixels in the large cloud pattern, followed by observed pixels and pixels in the small cloud pattern for the same image.

**Table S7.** Gradient boosted machine continuous FPC prediction results ordered by image date, by cloud pattern and pixel class for each date. The RMSE and MAE as percentages of mean FPC for each sample are in brackets. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image	Cloud	Pixel	Sample	DMCE	МАЕ
date	pattern	class	number	KIVI5E	MAE
	Small	Missing	1	14.787 (13.14%)	12.425 (11.04%)
	Small	Observed	1	16.116 (14.55%)	12.977 (11.71%)
	Large	Missing	1	14.839 (13.78%)	12.656 (11.75%)
16/7/00	Large	Observed	1	14.954 (13.25%)	12.487 (11.06%)
16/7/00	Small	Missing	2	15.430 (13.81%)	13.285 (11.89%)
	Small	Observed	2	16.066 (14.59%)	12.768 (11.59%)
	Large	Observed	2	14.794 (13.18%)	12.364 (11.01%)
	Large	Missing	2	16.859 (15.66%)	14.407 (13.38%)
	Small	Missing	1	12.891 (10.45%)	11.055 (8.62%)
	Small	Observed	1	14.143 (11.46%)	11.245 (9.11%)
	Large	Observed	1	12.970 (10.37%)	10.546 (8.43%)
2/0/00	Large	Missing	1	13.402 (10.77%)	10.974 (8.82%)
2/9/00	Small	Missing	2	12.561 (10.15%)	10.676 (8.62%)
	Small	Observed	2	14.004 (11.16%)	11.222 (8.94%)
	Large	Observed	2	13.163 (10.29%)	10.803 (8.44%)
	Large	Missing	2	13.375 (10.81%)	10.983 (8.88%)
	Small	Missing	1	7.930 (6.42%)	6.386 (5.17%)
	Small	Observed	1	10.385 (8.36%)	7.257 (5.84%)
	Large	Missing	1	8.061 (7.49%)	6.304 (5.86%)
19/0/00	Large	Observed	1	9.248 (7.48%)	6.797 (5.50%)
16/9/00	Small	Missing	2	8.214 (6.66%)	6.731 (5.46%)
	Small	Observed	2	8.908 (6.97%)	6.872 (5.38%)
	Large	Observed	2	8.979 (7.25%)	6.674 (5.39%)
	Large	Missing	2	9.255 (7.45%)	7.239 (5.82%)

When predicting FPC values gradient boosted machine had an RMSE ranging from 7.93 to 16.86. Gradient boosted machine had the lowest RMSE for the 18 September 2000 image for missing pixels in the small cloud pattern, followed by missing pixels in the large cloud pattern for the same image. The method performed well consistently for both missing and observed pixels in the 18 September 2000 image. The highest RMSE was for predicting FPC for missing pixels in the large cloud pattern in the 16 July 2000 image, followed by observed pixels and missing pixels for the same image. Gradient boosted machine predicted FPC with the largest RMSE for the July image overall. For random forest and gradient boosted machine, the methods had highest accuracy for the 18 September 2000 image for both binary classification and prediction of FPC values. This image has a majority of grassland class pixels.

Image date comparisons	Difference	p value
18/9/2000-16/7/2000	-5.7324	<.000
2/9/2000-16/7/2000	-1.4851	0.0219
2/9/2000-18/9/2000	4.2474	<.000

**Table S8.** Continuous FPC ANOVA results. Tukey posthoc comparison results showing differences in mean RMSE between image dates.

**Table S9.** Continuous FPC ANOVA results. Tukey posthoc comparison results showing differences in mean RMSE between methods.

Method comparisons	Difference	p value
IDW-GBM	-2.7537	0.0041
RF-GBM	-2.1736	0.0287
RF-IDW	0.5801	0.7645

Table S10. Two-way ANOVA results for differences in mean RMSE for continuous FPC.

Variable	F statistic	p value
Methods * Image date	1.1914	0.3233
Pixel class * Cloud pattern	3.0637	0.0846
Pixel class * Image date	1.1499	0.3229
Pixel class * Method	2.0680	0.155
Cloud pattern * Image date	0.1045	0.9009
Cloud pattern * Method	0.1090	0.7420

**Table S11.** Random forest accuracy results for continuous FPC predictions converted to binary class after analysis. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image date	Cloud pattern	Pixel class	Sample number	Overall accuracy	Converted overall	Converted producer's	Converted user's
	r	•••••		accuracy	accuracy	accuracy	accuracy
2/9/00	Small	Missing	1	0.820	0.668	0.102	0.978
	Large	Missing	1	0.814	0.698	0.148	0.977
	Small	Observed	1	0.773	0.671	0.096	0.977
	Large	Observed	1	0.771	0.668	0.066	0.992
	Small	Missing	2	0.719	0.666	0.085	0.990
	Large	Missing	2	0.708	0.698	0.039	0.960
	Small	Observed	2	0.702	0.656	0.063	0.987
	Large	Observed	2	0.701	0.660	0.065	0.994

For random forest we found a noticeable reduction in overall accuracy from a range of 0.701 to 0.820 for binary classification down to 0.66 to 0.67 by converting continuous FPC value predictions to a binary variable after initial analysis. These results indicate a substantial reduction in model accuracy as a result of converting a continuous FPC prediction to binary after analysis, rather than performing the conversion to a binary variable prior to performing analysis.

Image	Cloud	Pixel	Sample	Overall	Converted overall	Converted producer's	Converted user's
date	pattern	class	number	accuracy	accuracy	accuracy	accuracy
	Large	Missing	1	0.786	0.698	0.148	0.977
	Small	Missing	1	0.785	0.668	0.102	0.978
	Small	Observed	1	0.739	0.671	0.096	0.977
2/0/00	Large	Observed	1	0.720	0.669	0.066	0.992
2/9/00	Small	Missing	2	0.707	0.666	0.102	0.978
	Large	Missing	2	0.707	0.698	0.148	0.977
	Large	Observed	2	0.693	0.660	0.066	0.992
	Small	Observed	2	0.688	0.656	0.063	0.987

For gradient boosted machine we also found a substantial reduction in overall accuracy by converting continuous FPC value predictions to a binary variable after initial analysis (see table S12).

**Table S13.** Inverse distance weighted interpolation method continuous FPC prediction results ordered by image date, by cloud pattern and pixel class for each date. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Image	Cloud	Pixel	Sample	DMCE	MAE	
date	pattern	class	number	KIVI5E		
	Small	Observed	1	13.925 (12.57%)	10.592 (9.56%)	
16/7/00	Small	Missing	1	14.747 (9.55%)	12.325 (7.54%)	
	Large	Observed	1	11.070 (9.81%)	8.648 (7.66%)	
	Large	Missing	1	15.954 (10.28%)	13.492 (8.23%)	
	Small	Observed	2	13.890 (12.61%)	10.165 (9.23%)	
	Small	Missing	2	14.393 (9.53%)	12.377 (7.57%)	
	Large	Observed	2	12.106 (10.79%)	9.779 (8.71%)	
	Large	Missing	2	16.446 (10.47%)	14.097 (8.53%)	
	Small	Observed	1	12.475 (10.11%)	9.111 (7.38%)	
2/9/00	Small	Missing	1	12.114 (7.18%)	10.198 (5.74%)	
	Large	Observed	1	11.239 (8.99%)	8.599 (6.88%)	
	Large	Missing	1	12.829 (7.80%)	10.627 (6.19%)	
	Small	Observed	2	12.103 (9.64%)	9.073 (7.23%)	
	Small	Missing	2	11.659 (7.00%)	9.711 (5.52%)	
	Large	Observed	2	11.034 (8.62%)	8.426 (6.59%)	
	Large	Missing	2	12.672 (7.83%)	10.599 (6.31%)	
	Small	Observed	1	8.701 (7.01%)	5.442 (4.38%)	
18/9/00	Small	Missing	1	8.058 (4.02%)	6.408 (3.05%)	
	Large	Observed	1	7.697 (6.23%)	5.248 (4.25%)	
	Large	Missing	1	9.283 (5.19%)	7.075 (3.83%)	
	Small	Observed	2	6.948 (9.48%)	5.037 (7.10%)	
	Small	Missing	2	7.444 (4.08%)	6.057 (3.11%)	
	Large	Observed	2	7.331 (5.92%)	5.004 (4.04%)	
	Large	Missing	2	9.194 (4.31%)	6.999 (3.18%)	

**Table S14.** Inverse distance weighted interpolation method accuracy results for converted continuous FPC predictions to binary classification by image date, by cloud pattern and pixel class for each date. Sample number indicates which sample for each image the result refers to; we performed training, testing and accuracy assessment process on two random samples of observed pixels and two random samples of missing pixels per image under each of the different cloud patterns (6 images and 24 samples).

Imago	Cloud	Pixel class	Sample number	Converted	Converted	Converted
dato	pattern			overall accuracy	producer's	user's
uale				overall accuracy	accuracy	accuracy
16/7/00	Small	Missing	1	0.725	0.976	0.184
	Small	Observed	1	0.723	0.949	0.324
	Large	Missing	1	0.646	0.977	0.102
	Large	Observed	1	0.788	0.966	0.444
	Small	Missing	2	0.716	0.970	0.155
	Small	Observed	2	0.740	0.946	0.367
	Large	Missing	2	0.641	0.982	0.073
	Large	Observed	2	0.735	0.952	0.309
	Small	Missing	1	0.674	0.967	0.139
2/9/00	Small	Observed	1	0.787	0.905	0.567
	Large	Missing	1	0.686	0.986	0.091
	Large	Observed	1	0.721	0.952	0.292
	Small	Missing	2	0.735	0.946	0.356
	Small	Observed	2	0.735	0.946	0.356
	Large	Missing	2	0.688	0.986	0.100
	Large	Observed	2	0.743	0.950	0.373
	Small	Missing	1	0.839	0.725	0.911
18/9/00	Small	Observed	1	0.835	0.648	0.924
	Large	Missing	1	0.794	0.156	0.982
	Large	Observed	1	0.847	0.754	0.898
	Small	Missing	2	0.835	0.780	0.868
	Small	Observed	2	0.837	0.679	0.916
	Large	Missing	2	0.816	0.252	0.977
	Large	Observed	2	0.851	0.765	0.900



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).