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Supplementary materials: A comprehensive framework for assessing the accuracy and uncertainty of global above-ground biomass maps

Table S1. Metadata of the plot dataset.

ID	Scale	Type	Count	Avg. year	inventory	Avg. size (ha)	Avg. AGB (Mg ha -1)	Dominant biome	Reference
AFR2	Regional	Reseach plot	593	2007		0.69	118.51	Tropical rainforest	Lindsell and Klop (2013)
AFR4	Local	Reseach plot	110	2005		0.25	13.72	Tropical mountain system	De Vries et al. (2012)
AFR5	Local	Reseach plot	71	2008		0.16	118.6	Tropical rainforest	Laurin et al. (2016)
AFR6	Local	Reseach plot	24	2008		0.54	358.85	Tropical rainforest	Willcock et al. (2014)
AFR7	Local	Reseach plot	19	2008		0.64	32.58	Tropical rainforest	Lewis et al. (2013)
AFR8	National	NFI	105	2010		0.25	187.67	Tropical moist forest	Carreiras et al. (2012)
AFR9	Local	Reseach plot	41	2006		0.12	164.16	Tropical dry forest	Carreiras et al. (2013)
AFR10	Local	Reseach plot	18	2012		0.13	216.29	Tropical rainforest	Mitchard et al. (2011)
AFR11	National	NBS*	726	2012		0.08	266.36	Tropical rainforest	Drichi (2003); Avitabile et al. (2012)
AFR12	National	NFI	108	2009		0.67	371.28	Tropical rainforest	Avitabile et al. (2012)
AFR13	Local	Reseach plot	25	2012		1	243.52	Tropical rainforest	Mitchard et al. (2009)
AFR14	Local	Reseach plot	88	2008		0.13	70.37	Tropical dry forest	Mitchard et al. (2009)
AFR15	National	NFI	680	2011		0.13	25.35	Tropical mountain system	Vieilledent et al. (2016)
AFR FOS	Regional	Reseach plot	527	2013		0.44	287.77	Tropical rainforest	Schepaschenko et al. (2019)
ASI CH	National	NFI	1267	2008		0.1	129.39	Subtropical mountain system	Zhang et al. (2019)
ASI FOS	Local	Reseach plot	15	2006		0.4	308.6	Tropical rainforest	Schepaschenko et al. (2019)
ASI IND	Local	Reseach plot	96	1996		1	272.43	Tropical rainforest	Ramesh et al. (2010)
ASI PH	National	NFI	1210	2004		0.43	58.04	Tropical rainforest	Araza et al. (2021)
ASI1	Regional	NFI	2903	2008		0.05	108.19	Tropical mountain system and rainforest	Avitabile et al. (2016)
ASI2	Local	Reseach plot	119	2011		0.11	181.03	Tropical dry forest	WWF and OBf, 2013
ASI3	Local	Reseach plot	92	2007		1	163.45	Tropical rainforest	Morel et al. (2011)
ASI4	Local	Reseach plot	70	2010		0.02	208.48	Tropical dry forest	Wijaya et al. (2015)
ASI5	Local	Reseach plot	28	2015		3.07	35.93	Tropical rainforest	Slik et al. (2013)
ASI8	Local	Reseach plot	31	2008		0.02	304.81	Tropical dry forest	Murdiyarso et al. (2009)
ASI9	Regional	Reseach plot	74	2012		0.13	309.16	Tropical rainforest	Avitabile et al. (2016)
AUS FOS	Local	Reseach plot	3	2004		0.68	168.37	Tropical dry forest	Schepaschenko et al. (2019)
AUS INJ	National	NFI	5001	2000		0.25	76.66	Subtropical steppe	Tickle et al. 2016
AUS1	National	NFI	9113	2008		0.13	268.57	Tropical dry forest	Auscover (2016)
CAM FOS	Local	Reseach plot	19	2012		0.97	248.66	Tropical rainforest	Schepaschenko et al. (2019)
CAM1	National	NFI	4045	2006		0.16	82.3	Tropical dry/moist/rain forest	de Jong (2013)
EU FOS	Regional	Reseach plot	170	2014		0.27	194.02	Boreal coniferous forest	Schepaschenko et al. (2019)
EU1	National	NFI	16819	2011		0.01	76.37	Temperate broadleaf and Boreal forests	NA
EU2	National	NFI	58185	2003		0.2	60.45	Mediterranean forests	NA
EU3	National	NFI	3021	2013		0.06	190.98	Temperate oceanic forest	Schelhaas et al. (2014)
EU4	National	NFI	5967	2007		0.06	176.07	Temperate broadleaf and Mediterranean forests	NA
NAM1	National	NFI	588	2010		0.04	96.01	Boreal coniferous forest	Liang et al. (2015)
NAM2	Local	Reseach plot	75	2004		0.04	293.55	Temperate mountain system	Luyssaert et al. (2008)
NAM3	Regional	NFI	586	2010		0.03	130.93	Temperate continental forest	NA
NAM4	Regional	NFI	2798	2010		0.04	79.42	Temperate continental forest	NA
SAM FOS	Regional	Reseach plot	161	2010		0.47	333.25	Tropical rainforest	Schepaschenko et al. (2019)
SAM2	National	Reseach plot	281	2013		0.34	208.65	Tropical rainforest	dos Santos et al. (2019)
SAM3	National	NFMS**	111	2011		0.13	395.3	Tropical rainforest	Brown et al. (2014)
SAM4	Local	Reseach plot	7	2014		0.15	352.51	Tropical rainforest	Goodman et al. (2013)
SAM5	Local	Reseach plot	23	2014		0.6	144.11	Tropical rainforest	NA
SAM TAP	Local	Reseach plot	46	2009		0.25	217.71	Tropical rainforest	Bispo et al. (2014)
SAM BAJO	Local	Reseach plot	122	2017		0.26	74.52	Tropical rainforest	a Pacheco-Pascagaza et al. (2018)

*National Biomass System; **National Forest Monitoring System; both comparable to NFIs

Table S2. Summary statistics of plot data per major climatic zone and continent used for 2000, 2008/10, and 2017 map comparisons, respectively.

Major climatic zone and continent	Plot (n)	Avg. year	Avg. size $\pm SD(ha)$	Avg. AGB (min. - max) (Mg ha^{-1})
Boreal	**5783**	**2008.5**	**0.02 ±0.06**	**56.4 (0 - 360.4)**
Europe	5443	2008.5	0.02 ±0.06	54.1 (0 - 360.4)
N.America	340	2009.0	0.04 ±0	93.3 (0.1 - 247.2)
Subtropical	**56880**	**2003.4**	**0.19 ±0.04**	**55.8 (0 - 1212.5)**
Asia	1149	2008.0	0.1 ±0	114.6 (0.3 - 691.5)
Australia	3938	2001.8	0.2 ±0.1	113 (0 - 1212.5)
C.America	50	2006.0	0.16 ±0	50.8 (0.4 - 223)
Europe	51743	2003.6	0.19 ±0.02	45.2 (0 - 629.3)
Temperate	**17892**	**2005.8**	**0.11 ±0.08**	**133.8 (0 - 5676.1)**
Australia	1223	2007.4	0.08 ±0.04	298.4 (0.5 - 5676.1)
Europe	14480	2005.1	0.12 ±0.08	129.3 (0 - 973)
N.America	2189	2008.9	0.04 ±0.02	71.1 (0 - 937.1)
Tropical	**12307**	**2006.8**	**0.22 ± 0.42**	**109.7 (0 - 869.8)**
Africa	3534	2007.5	0.3 ±0.19	150.3 (0 - 863.1)
Asia	3900	2006.9	0.17 ±0.23	84.5 (0 - 830.9)
Australia	238	2005.3	0.32 ±1.62	31 (0 - 238.5)
C.America	3990	2006.0	0.16 ±0	67.3 (0 - 859.2)
S.America	645	2008.8	0.46 ±1.33	330.6 (18 - 869.8)

Major climatic zone and continent	Plot (n)	Avg. year	Avg. size $\pm SD(ha)$	Avg. AGB (min. - max) (Mg ha^{-1})
Boreal	**11865**	**2010.6**	**0.02 ±0.05**	**67.7 (0 - 429.4)**
Europe	11289	2010.6	0.02 ±0.05	66.2 (0 - 429.4)
N.America	576	2010	0.04 ±0.01	97.1 (0.2 - 273.4)
Subtropical	**63297**	**2003.7**	**0.19 ±0.05**	**79.6 (0 - 2096.4)**
Asia	1268	2008	0.1 ±0.01	131.5 (7.9 - 691.5)
Australia	9746	2003.2	0.19 ±0.11	138.4 (0 - 2096.4)
C.America	51	2006	0.16 ±0.01	70.3 (11.3 - 223)
Europe	52232	2003.6	0.19 ±0.02	67.4 (7.2 - 647.3)
Temperate	**26674**	**2008**	**0.09 ±0.12**	**179.9 (0.1 - 6822.4)**
Australia	2978	2010.7	0.08 ±0.1	475.9 (0.3 - 6822.4)
Europe	20290	2007.3	0.1 ±0.14	147.8 (0.2 - 1071.2)
N.America	3406	2009.8	0.04 ±0.02	93.2 (0.1 - 937.1)
Tropical	**14345**	**2007.4**	**0.25 ± 0.51**	**150.2 (0 - 1268.8)**
Africa	4285	2008.4	0.31 ±0.43	191.7 (0 - 980.6)
Asia	4449	2006.7	0.21 ±0.39	118.1 (2.1 - 1268.8)
Australia	316	2006.9	0.29 ±1.41	53.4 (0 - 276.2)
C.America	4006	2006	0.16 ±0.06	98.8 (16.2 - 865.2)
S.America	1289	2010.7	0.41 ±1.07	306.9 (1.5 - 876.8)

Major climatic zone and continent	Plot (n)	Avg. year	Avg. size $\pm SD(ha)$	Avg. AGB (min. - max) (Mg ha^{-1})
Boreal	**11661**	**2010.6**	**0.02 ±0.03**	**74.8 (3.7 - 437.1)**
Europe	11088	2010.6	0.02 ±0.03	73.3 (3.7 - 437.1)
N.America	573	2010.0	0.04 ±0	104.8 (7 - 281.9)
Subtropical	**21004**	**2006.8**	**0.18 ±0.06**	**101.9 (8.6 - 2103.4)**
Asia	1149	2008.0	0.1 ±0	136.4 (25.4 - 691.5)
Australia	2472	2009.7	0.14 ±0.15	186 (8.6 - 2103.4)
C.America	50	2006.0	0.16 ±0	83.9 (28.8 - 223)
Europe	17333	2006.3	0.19 ±0.04	87.7 (25.4 - 651.9)
Temperate	**20889**	**2009.6**	**0.06 ±0.13**	**204.7 (7.3 - 6823.9)**
Australia	2716	2011.3	0.08 ±0.1	519.8 (12.8 - 6823.9)
Europe	14970	2009.1	0.07 ±0.14	168.7 (7.3 - 1080.4)
N.America	3203	2010.0	0.04 ±0.01	105.8 (16 - 465.8)
Tropical	**11545**	**2008.1**	**0.22 ± 0.5**	**181.3 (7 - 991.5)**
Africa	3395	2009.2	0.32 ±0.22	234.1 (7 - 991.5)
Asia	3113	2008.2	0.09 ±0.4	139.3 (25.9 - 703.3)
Australia	217	2008.7	0.3 ±1.7	70.4 (20.4 - 283)
C.America	3609	2006.0	0.16 ±0.06	125.8 (43.5 - 862.8)
S.America	1211	2010.6	0.4 ±1.08	326.5 (27.1 - 883.8)

Table S3. List of global and pantropical biomass maps produced since the 2000 epoch.

AGBmap	Spatial scale	Forest mask data	Pixel size	Epoch	RS and in situ data	Open access (OA)	OA uncertainty layer	Reference
Avitabile	pantropical	-	1km	2000-2008	Fusion of Saatchi and Baccini Pan-trop	Yes	Yes	Avitabile et al. (2016)
Baccini Global	global	GLAS data and tree canopy cover thresholds	30m	2000	GLAS, MODIS, SRTM	Yes	Yes[1]	GlobalForestWatch (2002)
Baccini Pan-tropical	pantropical	-	1km	2007-2008	GLAS, MODIS, SRTM	Yes	Yes	Baccini et al. (2012)
Chen	global	GLC2000 forest and VCF threshold	1km	2007-2008	MODIS-NBAR	No	No	Chen et al. (2018)
CCI Biomass	global	-	100m	2017	ALOS2 PALSAR2, Sentinel 1	Yes	Yes	Santoro and Cartus (2019)
Hu	global	MODIS Land Cover	1km	2004	GLAS, MODIS, SRTM	No	No	Hu et al. (2016)
Kindermann	global	FRA forest area	55km	2005	FAO statistics, modelled NPP	No	No	Kindermann et al. (2008)
Liu	global	MODIS Land Cover forest	27.5km	1993-2012	L-VOD	No	No	Liu et al. (2015)
GEOCARBON	global	GLC2000 forests	1km	2008	Fusion of Avitabile and Santoro	Yes	Yes	Avitabile et al. (2014); Santoro et al. (2015)
GlobBiomass	global	-	100m	2010	ALOS-PALSAR, ENVISAT, ASAR	Yes	Yes	Santoro et al. (2020)
Ruesch-Gibbs	global	GLC2000 forests	1km	2000	GLC2000, IPCC data	No	No	Ruesch and Gibbs (2008)
Saatchi	pantropical	-	1km	2000	GLAS, MODIS, QSCAT, SRTM, forest plots	No	No	Saatchi et al. (2011)
Yang	global	Per continent based on secondary data	1km	2005	VCF, GLASS LAI, forest plots, regional maps	No	No	Yang et al. (2020)
Zhang	global	GFC tree cover threshold	1km	2000	Fusion of local and global maps	No	No	Zhang and Liang (2020)

[1] Currently accessible at Google Earth Engine (https://code.earthengine.google.com/11b2fe70fd7019cd70fafa375bb3a525), but will be re-uploaded to its original repository at global forest watch platform.

Fig. S1. Comparison of the assessments when using the grid cells from the current approach and after strict filtering to mitigate preferential sampling. The latter involved the following steps: (1) Use of the plot dataset used to assess the 2010 GlobBiomass map, and the 30-m Hansen 2010 tree cover (TC) as a proxy for AGB variability (Avitabile and Camia, 2018). (2) Compute the mean TC of the grid cell and at plot locations, and their difference (mean plot TC – mean grid cell TC). The standard error of the mean TC at plot locations is also computed. Assuming the difference is normally distributed, a grid cell is accepted if the mean of the exhaustively sampled TC is within the 90% confidence interval of the true mean TC. (3) Assess the effect of preferential sampling through GlobBiomass assessments using grid cells from strict filter and the current approach. The slight differences between the two comparisons, even for the >300 Mg ha^{-1} bins, indicate that preferential sampling is unlikely to have much impact on our analysis. This can be attributed to our use of more NFIs than research plots and the fact that many of the research plots used are within forests which visually exhibit homogeneous canopy cover.

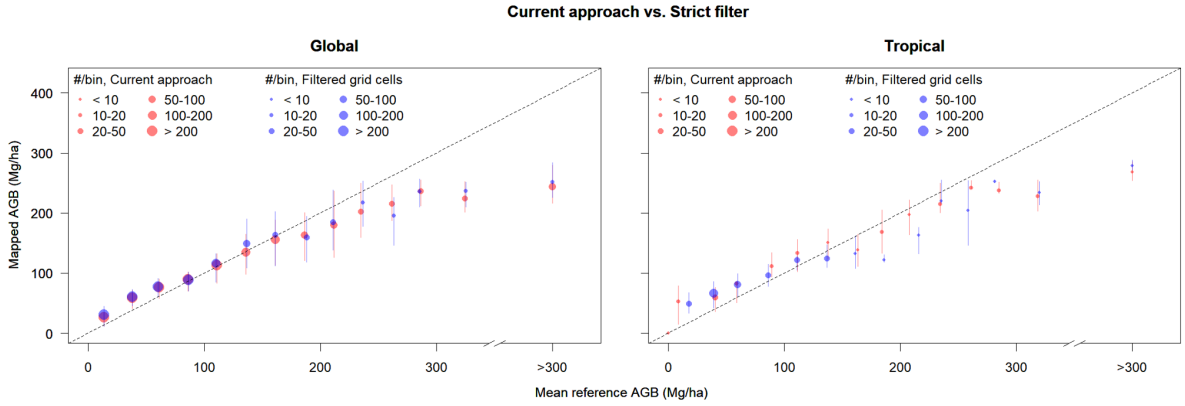


Fig. S2. Locations of all possible pantropical grid cells and those selected under both the current approach and strict filtering in high AGB tropical areas wherein 77% of the grid cells chosen under the current approach are also chosen after strict filtering. The average number of plots inside selected 0.1° grid cells is 10.89 for the current approach and 11.59 for the strict filter.

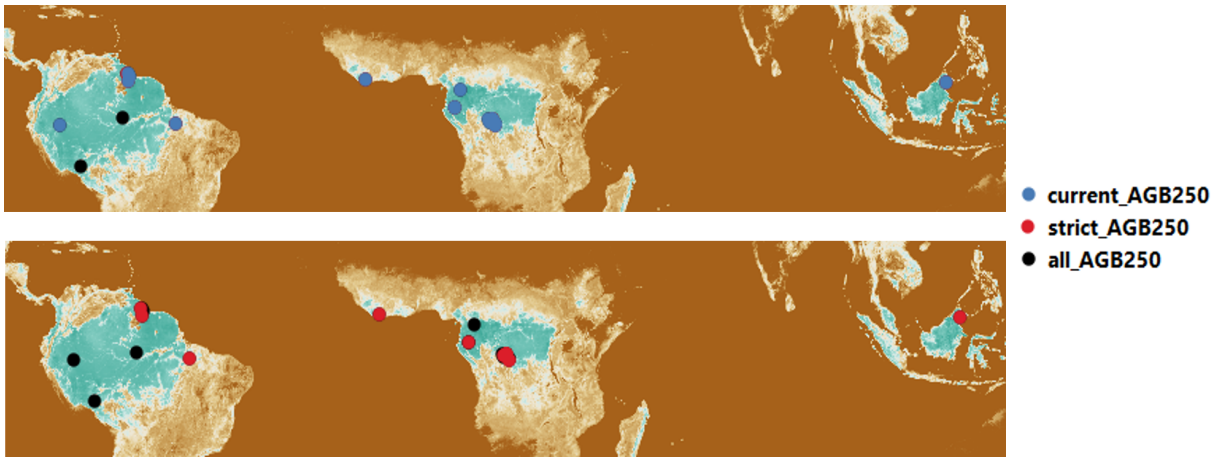


Table S4. Summary results for the weighted RF models used for bias modelling with the explained trend (%) and the rank and percentage of the Variable Importance Measure (VIM) values per covariate. The covariates in the Baccini model exclude the SD layer (currently only available for the pantropics) to enable global bias prediction.

RF model	Explained trend (%)	VIM rank	VIM proportion (%)
Baccini	36	Above-ground Biomass map (AGB), Tree Cover (TC), Slope (SL), Aspect (ASP)	49,32,12,7
GEOCARBON	24	AGB, TC, Standard Deviation layer (SD), SL, ASP	30,27,17,15,11
GlobBiomass	27	TC, AGB, SD, SLP, ASP	27,26,19,17,11
CCI Biomass	33	AGB, TC, SD, SL, ASP	26,22,19,17,17

Fig. S3. Partial Dependence Plots of predicted bias as a function of a covariate pair in the CCI Biomass map: (a) AGB map and tree cover at 0.1° ; and (b) slope and aspect at original map pixel size of 100 m.

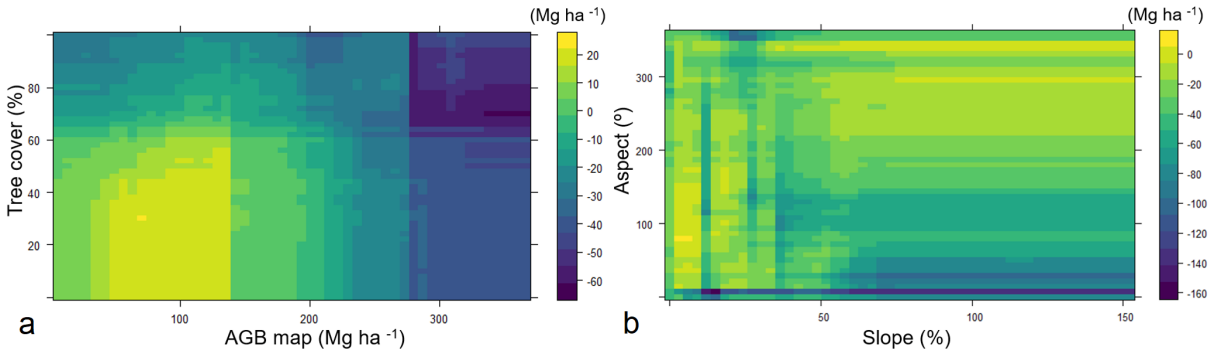


Fig. S4. Plot-to-map comparison for the bias-corrected AGB maps indicating an increase in map accuracy (relative to Fig. 4). The comparisons used a third of the total grid cells, independent to the ones used for the bias modelling: Baccini=2165, GEOCARBON=2152, GlobBiomass=2046 and CCI Biomass=862. Each circle represents an AGB bin and its size indicates the number of plot data while the whiskers correspond to the 25^{th} and 75^{th} quartile range of the map AGB.

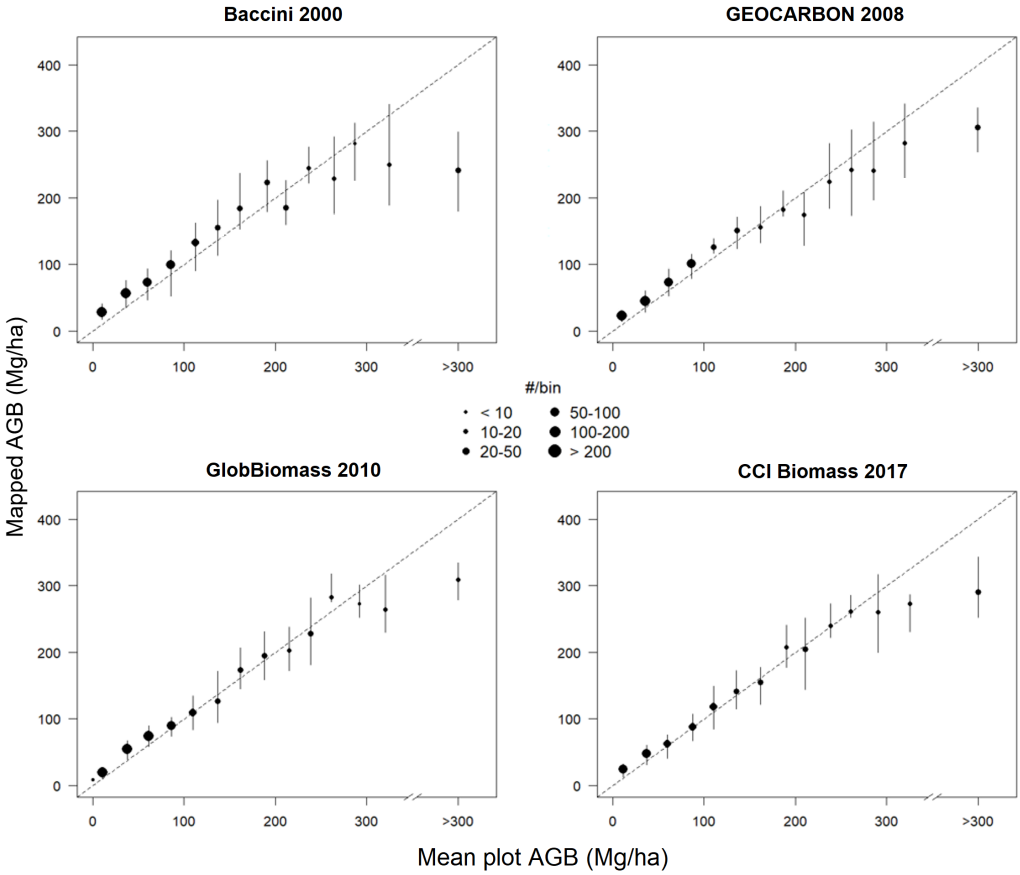


Fig. S5. Variogram models (VMs) fitted to data from the four AGB maps: (1) default VMs, (2) VMs adjusted by plot measurement error, and (3) convoluted VMs.

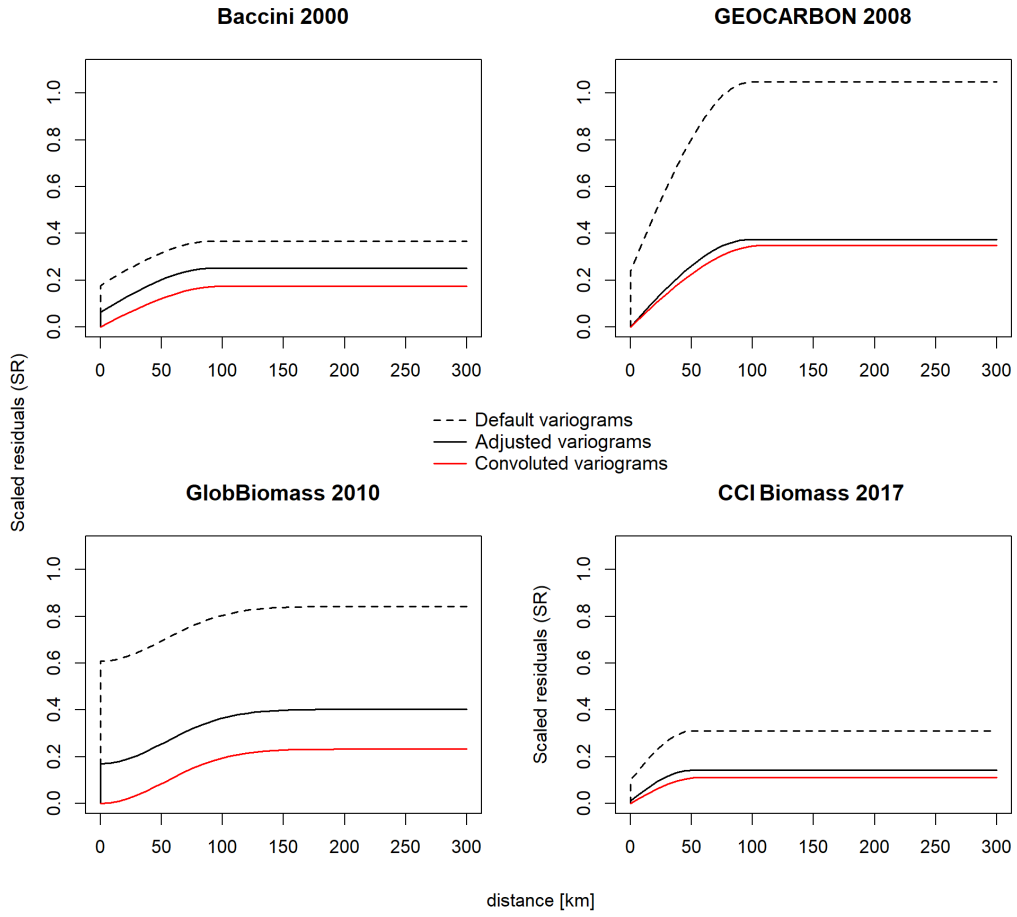
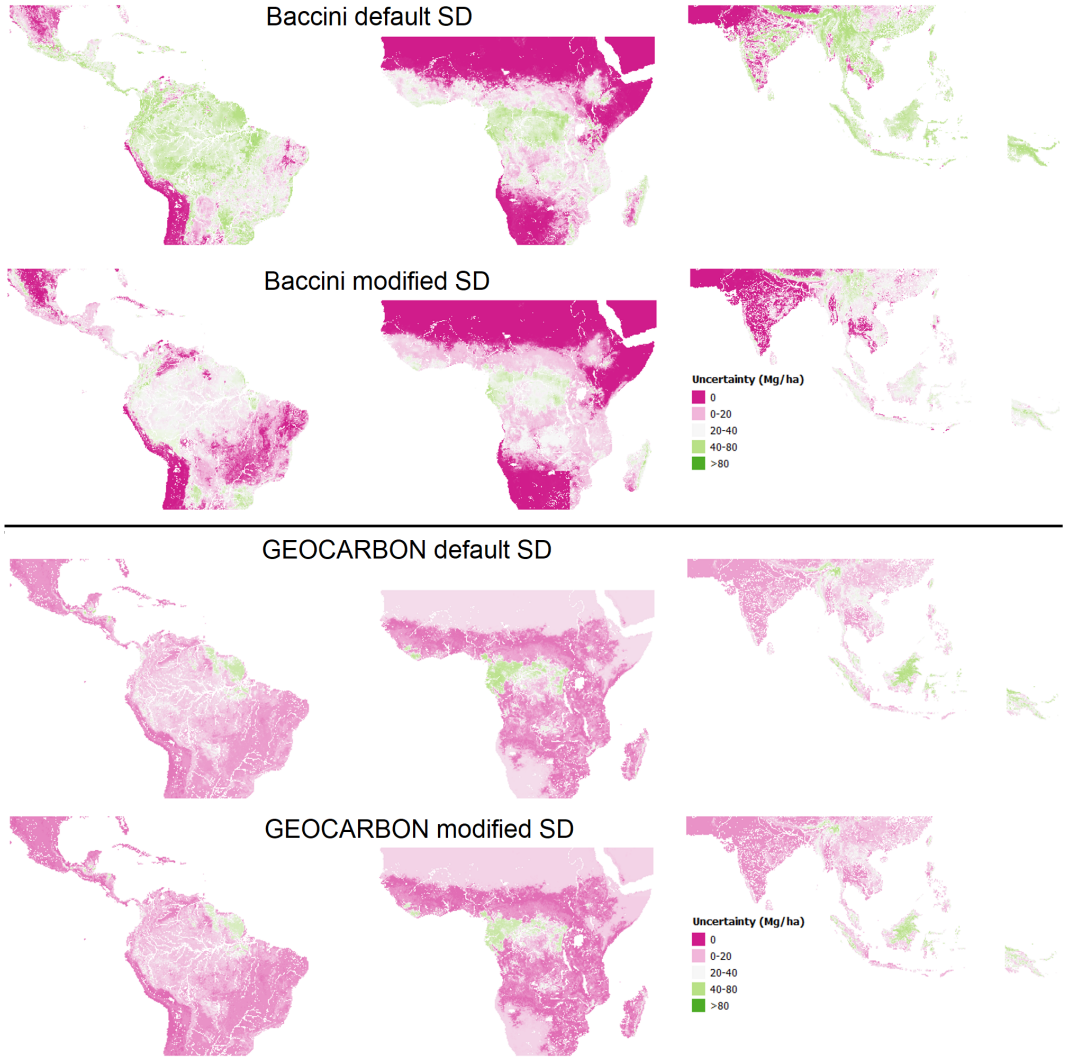
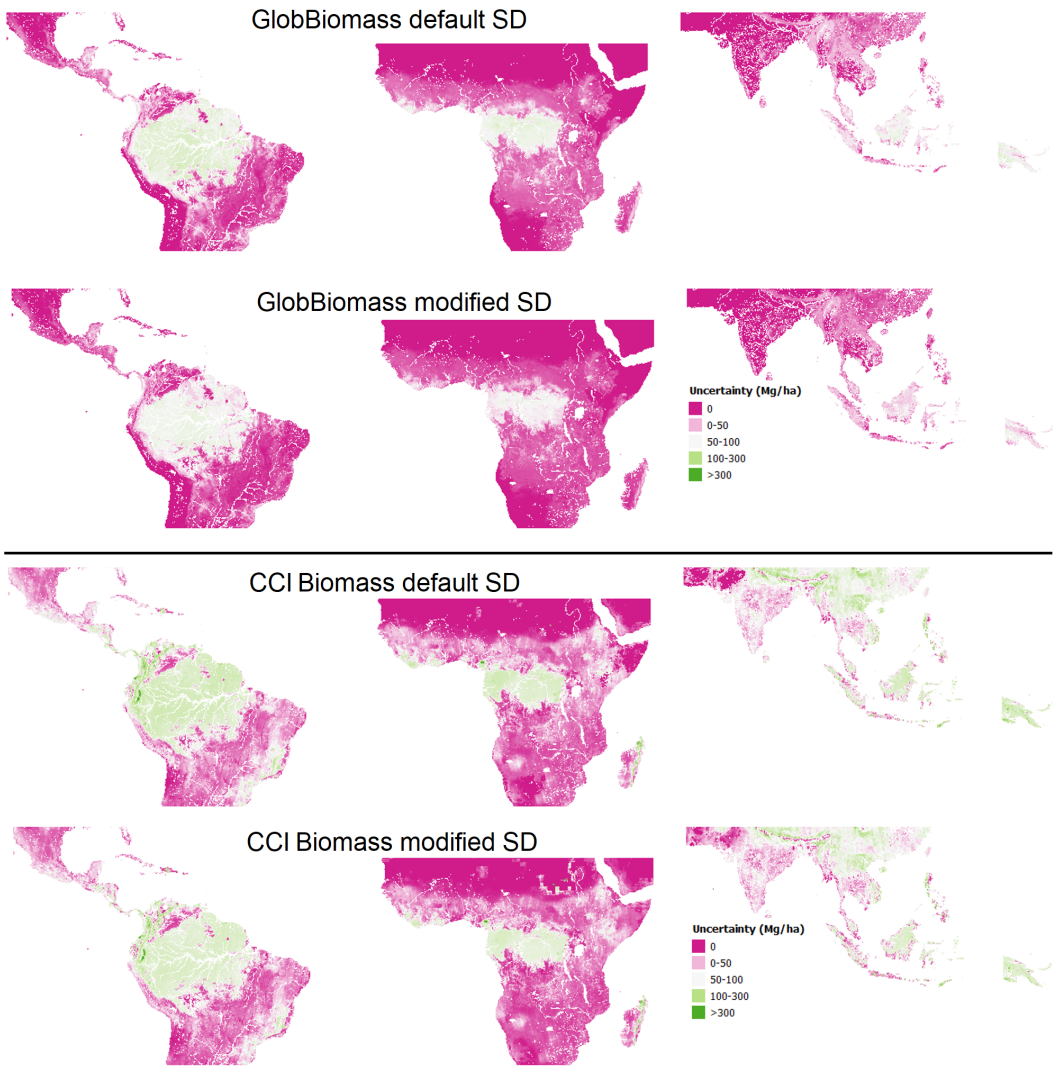


Fig. S6. The SD layers at original map pixel size (default SD) and the modified SD layers at 0.1° used for uncertainty aggregation in the pantropics. The modified maps account for spatial autocorrelation when averaging from original map resolution to 0.1°.





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