CCI

BIOMASS

PRODUCT VALIDATION & INTERCOMPARISON REPORT

VERSION 7.0

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SYMBOLS AND ACRONYMS

AGB	Aboveground biomass
AGB_{map}	Aboveground biomass according to the map
AGB_{ref}	Aboveground biomass from plot, corrected for plot inventory date and if plot size < 1 ha, corrected for partial forest fraction at pixel level
CCI	Climate Change Initiative
CoFor	Congo basin Forests AGB dataset (Ploton *et al*., 2020)
GNSS	Global Navigation Satellite System
IPCC	Intergovernmental Panel on Climate Change
I_{Var}	Indicator variable: 1 if the SE_{CCI} is consistent with (Plt), MD and MSD, and 0 otherwise. The latter indicates that the SE_{CCI} layer is overly pessimistic regarding AGB map precision.
LiDAR	Light Detection And Ranging
MD	Mean difference between AGB_{map} and AGB_{ref}
MSD	Mean square difference (between AGB_{map} and AGB_{ref})
NEON	National Ecological Observatory Network, USA
NFI	National Forest Inventory
PUG	Product User Guide (Santoro, 2020)
PVIR	Product Validation and Inter-comparison Report
PVP	CCI Biomass Product Validation Plan
RMSD	Root mean square difference (between AGB_{map} and AGB_{ref})
SE_{CCI}	Error layer (standard deviation) provided with the CCI Biomass product; if squared denoted as SE_{CCI}^2.
SLB	Sustainable Landscape Brazil
SRTM	Shuttle Radar Topography Mission
TERN	Terrestrial Ecosystem Research Network, Australia
Var(Plt)	Estimated variance of the plot measurement error
Var(S(x))	Estimated variance of the within-pixel sampling error (owing to smaller plot footprint)

1. Introduction

Validation is critical for increasing acceptance of satellite-derived products by user communities (e.g., carbon cycle science, climate modelling). To assess the accuracy of the aboveground biomass density (AGB; Mg/ha) estimates for the covered epochs of the refined CCI Biomass global products (Santoro, 2024), AGB predictions from the map have been compared with independent AGB data from plots and LiDAR campaigns, which were used as reference values. The main aim of this report is to provide an independent assessment of the quality of the CCI Biomass products generated in Year 7 of the project, with this primarily providing (climate) users with uncertainty information, which includes both precision and bias, when using the map, including for global and regional climate modelling and assessment purposes. A second purpose is to provide feedback to map producers to establish where the maps can be improved.

The reference AGB data are not error-free. *In situ* estimates of AGB are computed based on stem diameter (typically cm), tree height (m), wood density (g cm^3) and allometric models, while geolocation is determined using Global Navigation Satellite System (GNSS) measurements that have variable and often limited accuracy. GNSS accuracy is degraded if the paths between the satellites and the GNSS receiver are partly blocked by vegetation cover, which is not uncommon in forests. An additional cause of discrepancies between plots and pixel-based AGB estimates is the difference in support (shape and size) between map pixels and plots. The latter are often much smaller than the areas of the pixels they are being compared with, which may introduce two types of error. The first is a *sampling error*, since an estimate of the AGB in only part of the pixel area (the plot) is being compared with that of the full pixel area. Secondly, and more subtly, a *representation error* can occur if plots are selected with particular properties, such as only being from mature forest despite being in a mixed age forest which results in them not being representative of the forest population. This type of representation error is often termed *selection bias*. Both types of error can occur even if the pixel's footprint is fully covered by forest, largely because of AGB heterogeneity inside the pixel. There may also be a representation error if, for example, a forest plot is used to represent a pixel that is only partially forested. Additionally, the plot inventory date often differs from the biomass map epoch, which gives a temporal mismatch between the compared AGB values.

LiDAR-based AGB estimates used as reference data can completely cover map pixels or even larger pixel blocks, which minimizes the sampling errors referred to above. However, as with *in situ* estimates of AGB, LiDAR-based AGB values are themselves predictions, so are subject to prediction errors that must be considered.

Each of the above-mentioned factors can introduce errors with a random or a systematic nature. The systematic error is of particular concern since it cannot be reduced by aggregating individual tree measurements over large plots or by averaging small plot data over many plots. Systematic errors in reference data have to be reduced as much as possible by adhering to a standardized measurement protocol (CEOS, 2021).

The five versions of the CCI Biomass Product Validation Plan (PVP; de Bruin *et al.*, 2019a, 2020, 2021, 2022) presented approaches for addressing the temporal mismatch between plot and pixel data and partial forest fractions within map pixels. The reports also proposed methods for assessing the variance of the other error sources. In this seventh PVIR, the temporal mismatch between plot and pixel data and partial forest fractions within map pixel are handled similarly to the first six PVIRs. The proposed approaches for accounting for other error sources are partly implemented, up to the point supported by available data.

An extensive dataset of forest plot data across the world was acquired for the purpose of the validation (see Appendix A,

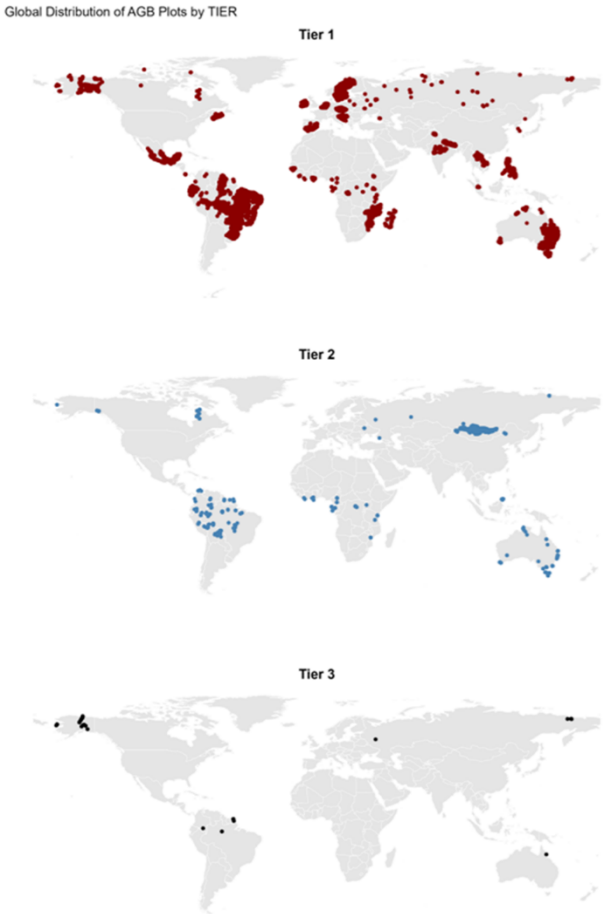

Figure 1 and Table 1). As before, the plots underwent a series of quality checks (see Section 2.1). Forest plot data and LiDAR were not used to calibrate the CCI Biomass map in order to guarantee full independence from the production process. The contributions of AGB measurement error and spatial representation error are known to be largest for small plots, such as those typical of National Forest Inventories (NFIs), while detailed measurements of all trees within large plots are expected to deliver the highest quality AGB data (Réjou-Méchain *et al.*, 2019; Réjou-Méchain *et al.*, 2014). To take into account expected differences in the accuracy of plot data, a tiered approach was chosen which comprised:

- Tier 1 - small plots (≤ 0.6 ha), including NFI data,
- Tier 2 - larger plots (0.9-3 ha; Tier 2), and
- Tier 3 - high-quality large super-plots (≥ 6 ha; mainly from Labrière *et al*. (2018)).

The Tiers were analysed separately in the plot-pixel comparisons. AGB map comparisons with data derived from LiDAR and aggregated plot data (see Section 2.2) were also analysed separately.

The map inter-comparison presented in this document concerns consistency of map-reference deviations amongst the CCI Biomass AGB products and comparisons with Version 6 of the CCI Biomass products of the same epochs (Santoro, 2021). Results from two external map inter-comparisons, as examples of user-led independent validation, are also included. Lastly, the CCI maps are inter-compared with other AGB map products.

2. Materials and methods

2.1.Forest plot data

For CCI Biomass, new forest inventory and plot data from research networks were added to the previously established GlobBiomass reference database (Rozendaal *et al.*, 2017). Additional reference data were collected during the span of the CCI Biomass project focusing on potentially under-represented areas, i.e., forests in boreal and mountainous regions. Reference data were only included if quality criteria, as described in the PVP, were met. Specifically, the plots needed:

- A citable reference source and metadata to assess the procedures and quality of biomass estimation.
- Precise coordinates (4-6 decimals for coordinates in decimal degrees of plot centroids).
- A census date within ten years of the reference year of the AGB map to avoid temporal inconsistency with the assessed maps.
- Inclusion of measurements of all trees of diameter at breast high ≥ 10 cm (or less).
- To have experienced no deforestation between the year of the inventory and the reference year of the CCI Biomass map (i.e., 2010; and 2017-2020). This was assessed based on the forest loss layer of the Hansen dataset (Hansen *et al.*, 2013).

The number of usable reference plots varied across map years, with the largest pool occurring around the central reference years (2010-2015) due to the temporal criteria (third bullet).

Table 1. Number of plots used in each Tier for the different AGB map reference years.

Map ref. year	Tier1	Tier2	Tier3	Total
2005	85693	4106	111	89910
2006	93393	4178	129	97700
2007	99197	4179	129	103505
2008	103033	4213	129	107375
2009	104418	4263	129	108810
2010	104609	4263	129	109001
2011	105253	4282	129	109664
2012	107022	4282	249	111553
2015	107803	4282	249	112334
2016	107803	4282	249	112334
2017	96842	4218	249	101309
2018	81536	4067	249	85852
2019	73332	3978	247	77557
2020	68620	3956	230	72806
2021	63792	3932	228	67952
2022	58326	3906	228	62460
2023	48500	3717	211	52428
2024	40794	3683	208	44685

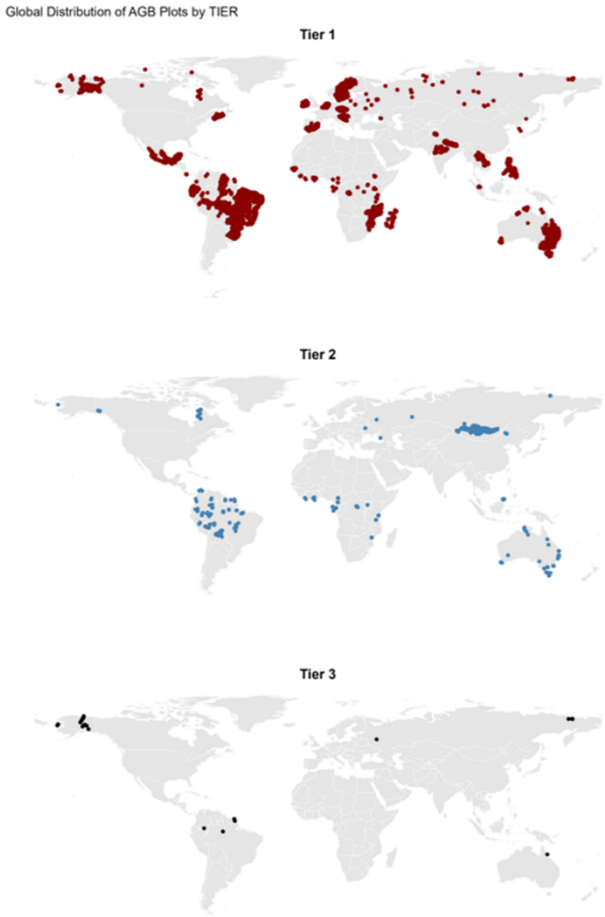

Figure 1. Geographical locations of plots and footprints of the reference datasets grouped per tier used to assess the 2010 biomass map

2.2. AGB estimates from LiDAR, Congo basin management inventories, and US Forest Service plots

In addition to the plot data, we used airborne LiDAR-based AGB data at 100 m resolution from the Sustainable Landscape Brazil project (SLB), the National Ecological Observatory Network, USA (NEON) and the Terrestrial Ecosystem Research Network, Australia (TERN), which were processed by Labrière and Chave (2020a, b, c); a dataset from the Piñon-Juniper woodlands in the USA; the Rodda *et al*. (2022) dataset from Africa and Asia ALS missions; the EBA-ALS in Amazonia (Csilik *et al*., 2024). This EBA-ALS dataset comprises the bulk of the LiDAR-based validation data for the current validation exercise. The 1-km pixel forest management inventory data used in this report originated from the Congo basin Forests AGB (CoFor) dataset (Ploton *et al*., 2020). For the CoFor dataset, only pixels having at least five *in situ* forest management inventoried plots were used. Lastly, we used the Environmental Monitoring and Assessment Program (EMAP) AGB aggregates of 27-km hexagons estimated from the Forest Inventory and Analysis Program of the US Forest Service (Menlove and Healey, 2020), which was useful for the 2015-2024 comparative analysis. See

Table 2 and Figure 2 for the breakdown and geolocations of the Tier 0 reference data, respectively. Note that same with Tiers 1-3, the Tier 0 plots were subjected to the temporal criteria mentioned in Section 2.1.

Table 2. Number of LiDAR, CoFor and EMAP footprints used for the different AGB map reference years.

Map ref. year	CoFor	LiDAR	EMAP	Total
2005	24474	109106	2874	136454
2006	24474	149412	2874	176760
2007	24474	557180	2874	584528
2008	24474	607526	3874	635874
2009	24474	1565454	3874	1593802
2010	24474	1839014	3874	1867362
2011	24474	1839014	3874	1867362
2012	24474	1839014	3874	1867362
2015	24474	1839014	3874	1867362
2016	24474	1839014	3874	1867362
2017	24268	1839014	3874	1867156
2018	18712	1839014	3874	1861600
2019	17554	1839014	3874	1860442
2020	15136	1839014	3874	1858024
2021	13162	1839014	3874	1856050
2022	8292	1832528	3874	1844694
2023	2206	1803014	2874	1808094
2024	972	1794762	2874	1798608

As described in the PVPs, we rely on opportunistic AGB plot data that were not specifically produced for validation purposes but that were rather collected within the context of country NFIs and research efforts at local to regional scales.

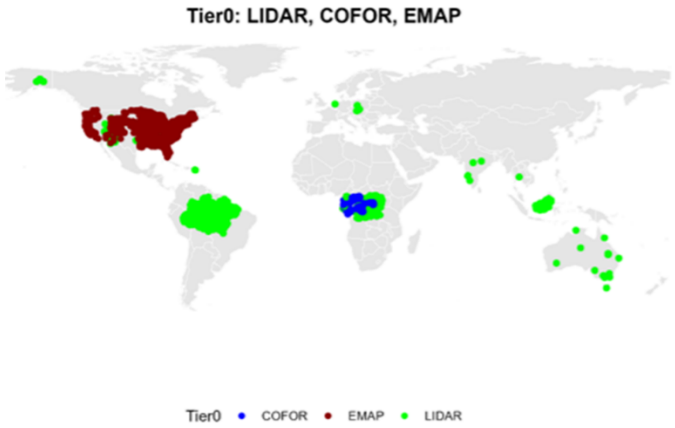

Figure 2. Geographical locations of plots and footprints of the reference datasets grouped per tier used to assess the

2.3.Increase of reference data from *Version* 6 to *Version* 7

The reference data used to assess CCI Biomass Version 7 has increased compared to the previous reference data used for the Version 6 maps. The validation team focused on acquiring new reference data in potentially under-represented regions (Labriere *et al*., 2022, Araza *et al*. Under review). The additions include NFI data from Ecuador, Mongolia, Laos; permanent plots in the Himalayan region

and Indonesian mangroves; and airborne LiDAR-based maps in Brazil and Europe. Unlike the previous additions acquired under data-use agreements, the new additions now are mostly open-source data; see Appendix A for further information.

2.4. Preparation of validation datasets

Temporal harmonization

Differences between the inventory date of AGB plots and the reference year of the AGB map were harmonized using updated IPCC growth rates (IPCC, 2019; Requena Suarez *et al.*, 2019) following the approach described in Version 1 of the PVP. For plots in tropical and subtropical ecological zones, age-category-dependent growth rates are available (IPCC, 2019; Requena Suarez *et al.*, 2019). In these cases, plot AGB values in the range 0-99 Mg/ha were assumed to represent young secondary forest, AGB values in the range 100-128 Mg/ha were treated as old secondary forest (Van Breugel *et al.*, 2007), and AGB above 129 Mg/ha was assumed to correspond to old-growth stands (Brown *et al.*, 1989; Clark & Clark, 2000; Mello *et al.*, 2016). Given the absence of data on plot forest age, mature forests of low biomass could not be distinguished from young stands with similarly low biomass, with potential implications for the growth rates applied. For temperate oceanic forests in Europe and boreal coniferous forests and tundra woodlands, no differentiation of growth rates over age categories was used. The temporal adjustments by growth rates were applied up to a difference of ten years between the inventory date and the map reference year. Plots having a longer temporal difference were discarded in the analyses. Some of the LiDAR dataset (NEON and SLB) were exempted from temporal adjustment because they have repeated measurements between 2011 and 2018.

Correction for forest fraction

As described in the PVP, correction for inclusion of non-forested areas within map pixels was undertaken by multiplying the temporally adjusted plot AGB by the forest fraction at the pixel level of 100 m. The forest fraction was computed by setting a 10% threshold on the 2010 tree cover product (Hansen *et al.*, 2013), which had a resolution of 1 arc-second per pixel, or approximately 30 meters per pixel at the equator. Moreover, tree cover datasets corresponding to 2015-2024 were produced for this purpose, removing associated deforestation pixels from an annual tree cover data using the annual forest loss product of Hansen *et al.*, 2013. In the rare case of more than one AGB plot within a hectare/CCI map pixel, the average of the adjusted AGB per plot was used. The correction for forest fraction was only applied to plots with an area below 1 ha.

Comparisons at 0.1° cell resolution

To reduce the effect of short-range AGB spatial variations in the map and their potential interaction with plot-map geolocation mismatches and to assess the CCI Biomass map at a resolution commonly used by climate modellers, AGB_{map} - AGB_{ref} comparisons from Tier 1 data were also made over multi-pixel blocks at 0.1° cell resolution. In this case, correction for partial forest fraction (see above) was undertaken at the level of the coarse resolution cells. The mean AGB_{ref} at 0.1° cell level was computed by multiplying the forest fraction at the 0.1° cell level by the mean temporally adjusted AGB of at least five plots in that cell. The procedure is illustrated in Figure 5 of the PVP (de Bruin *et al.*, 2019a). The choice to use a minimum number of plots inside grid cells was motivated by previous and recent studies e.g., Fazakas *et al.* (1999); Baccini *et al.*, 2012, Baccini *et al.*, 2017; Xu *et al.* (2021); and Araza *et al.* (2022a). The AGB reference values thus obtained were compared with the average map AGB spatially aggregated over the 0.1° cells. In the case of the EMAP dataset comparison, the map AGB was averaged to 0.25°.

The correction for forest fraction was not applied to the LiDAR dataset since the LiDAR footprints were assumed to representatively sample forest/non-forest fractions within the 0.1° cells, i.e., forested areas were not preferentially sampled.

Ecoregions / biomes

AGB_{map} - AGB_{ref} comparisons at 0.1° cell resolution were also stratified according to ecoregions derived from a recent global ecoregion map (Dinerstein *et al.*, 2017), which was downloaded from https://ecoregions2017.appspot.com/. The original vector maps were rasterized to 0.1° resolution. The resulting raster cells were assigned to the category covering the largest portion of the cell area. Comparisons were stratified from Tier 3 data at 0.1° cell resolution per biome.

2.5.Comparing AGB map pixels with reference data

Assumptions

After adjustments for temporal discrepancies and partial forest fraction and having at least ten plots within a reference AGB range, the unweighted means computed from reference data in Tiers 1 and 2 were assumed to be unbiased given that plot data were used where AGB was estimated using the most appropriate allometries by the data providers (Araza *et al*. 2022a) The AGB ranges used are listed in the first column of Table 3. For Tier 3 data, the requirement of ten plots per AGB range was relaxed because these data were recorded over large plots (≥ 6 ha) and followed a strict measurement protocol. Under the unbiasedness assumption, mean differences between harmonized plot data and map values aggregated over bins covering ranges of reference AGB values are interpreted as *map bias*. To empirically verify the assumption of unbiased plot data, the analysis was conducted for each of the three tiers and consistency of results between them was assessed, whenever this was allowed by the data volumes.

When reporting mean differences (MD) and root mean square difference (RMSD) over ecoregions, plot-map comparisons within ecoregions were assumed to be representative of those regions.

Measures

Besides reporting mean differences between reference and map AGB per biomass range, which are interpreted as map bias (see above), RSMD between map values and plots are reported. At this stage, the MSD was not interpreted *error* of the map since we will elaborate on the assessment of the variance of individual error components in later stages of the project. However, we did assess whether the mean variance of map error ($mean(SE_{CCI}^2)$)—where SE_{CCI} is the standard error layer provided with the CCI Biomass AGB map—is consistent with *MSD*, *MD* and the mean variance of plot measurement error $mean(Var(Plt))$. The SE_{CCI} layer only represents the random part of AGB errors and the aggregated SE_{CCI} layer at 0.1° already accounts for spatially correlated map errors identified using LiDAR datasets (Santoro, 2023b). Leaving out three random error components listed in the PVP (positional error, within-pixel representation error and the data harmonization error) and under the assumptions given above, we checked whether $mean(SE_{CCI}^2) \leq MSD - MD^2 - mean(Var(Plt))$.

For this purpose, we defined an indicator variable I_{Var}, as follows:

$$I_{Var} = \begin{cases} 1 \;\; if \; mean(SE_{CCI}^2) \leq MSD - MD^2 - mean(Var(Plt)) \\ 0 \quad otherwise \end{cases}$$

If I_{Var} has value zero, $mean(SE_{CCI}^2)$ would be too large or, in other words, the SE_{CCI} layer provided with the AGB product would be pessimistic about map precision, unless the variance of plot measurement error is greatly underestimated.

For plots having tree-level data, (Plt) was computed using the Réjou-Méchain *et al*. (2017) biomass R-package. For other plots lacking such data, $Var(Plt)$ was predicted by a random forest model trained on the plots having tree-level data, using plot biomass, plot size, general and specific eco-zones and continent as explanatory variables.

2.6.Spatial correlation of AGB

Experimental semi-variograms were computed and variogram models were fitted using *gstat* (Pebesma, 2004) based on LiDAR-AGB data acquired over two forest sites in Remningstorp, Sweden, and Lope, Gabon, i.e., a *boreal* and a *tropical* forest site. These ALS datasets were acquired in the framework of the airborne ESA BIOSAR (Ulander *et al*., 2011) and AfriSAR (Hajnsek *et al*., 2017) campaigns to provide detailed information on forest vertical structure and to produce high-resolution AGB maps. The AGB data have a spatial resolution of 10 m (Remningstorp) and 20 m (Lope) and were also used in Version 2 of the Product User Guide (PUG; Santoro, 2024). Non-forest areas (such as savanna in the Lope study area) were masked out after manually digitizing forested areas using high resolution Google Earth imagery. Accordingly, the variogram models represent spatial correlation of AGB within forested areas at the study sites.

2.7.Effect of spatial support on sampling error and suggested map bias

The variogram models described above were used to assess the effects of the within-pixel sampling error (see Introduction) for the forest sites in Remningstorp and Lope. This was undertaken by two means:

- By computing the variance of the difference between sub-pixel plots and plot configurations (i.e., for plots smaller than pixels) and AGB map pixels at locations *x* as:

$$Var(S(x)) = Var\left(AGB_{ref}(x) - AGB_{map}(x)\right) = Var(AGB_{ref}) + Var(AGB_{map}) - 2 * Cov(AGB_{ref}, AGB_{map}),$$

where $Var(AGB_{ref})$ is the sill of the variogram at the spatial support of the plots, $Var(AGB_{map})$ is the within-pixel covariance, and $Cov(AGB_{ref}, AGB_{map})$ is the plot to pixel covariance. Note that for brevity, reference to the location *x* is omitted in the right-hand side of the above equation. The latter two terms are computed using the geostatistical framework for change of support (Kyriakidis, 2010).

- By simulating possible plot AGB, conditional on given AGB values at the pixel level, using the $Var(AGB_{ref} - AGB_{map})$ computed in the above step. The aim of this simulation is to provide a proof of concept on the effect of within-pixel sampling error in the plot-map comparisons.

3. Validation results for the global maps

3.1. Global assessments per Tier of plot data

Tier 1 non-aggregated

An overall feature of the comparisons is the large scatter; this is expected, given that the left-side plots are small reference plots being compared to larger pixels without considering scaling effects. The plots showing binned ranges (right-hand side) show over-prediction for the low reference biomass and under-prediction of higher reference AGB values, while relative accuracy is within 25% in the middle range. On average, under-prediction by the map starts at a reference AGB of approximately 150 Mg/ha but the interquartile range of plot data still covers the 1:1 line between AGB_{ref} and AGB_{map} up to approximately 210 Mg/ha. All maps show under-prediction starting at around 130-160 Mg/ha. The AGB_{ref} values originate from small plots, some with exceptionally high AGB that is unlikely to cover extensive areas and are unlikely to be captured by the AGB retrieval algorithm. These plot data are also dominated by data from several countries from subtropical and temperate regions (Figure 1). The banding observed in the left column of Figure 3 especially for the 2010 map seems to be caused by a maximum AGB level set for particular regions in the retrieval algorithm. A first impression is that the accuracy of the current map versions has been affected by the maximum AGB and has improved in several regions compared to the previous edition reported in de Bruin *et al*. (2022b: Table 4 and Figure 4 therein). This is further analyzed in Section 3.7.

For AGB bins > 200 Mg/ha in Table 3-20, the indicator variable I_{Var} = 1, suggesting the SE_{CCI} layer provided with the AGB product is optimistic about the precision of the CCI Biomass maps. The considerable mean variance of plot measurement error, $mean(Var(Plt))$, of the smallest plot size category, definitely contributes to this observation. Further analyses of the random error components are needed to assess whether the reported SE_{CCI} for AGB_{ref} > 400 Mg/ha is indeed reasonable. There seems to be an artefact from the reference data from 2005 to 2012 for bin 180 Mg/ha.

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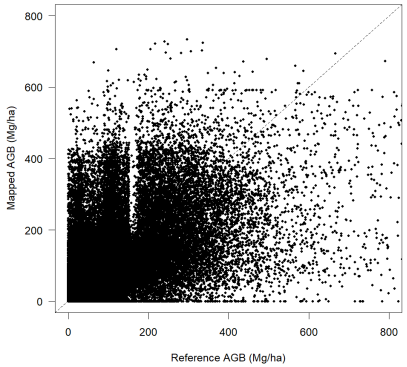
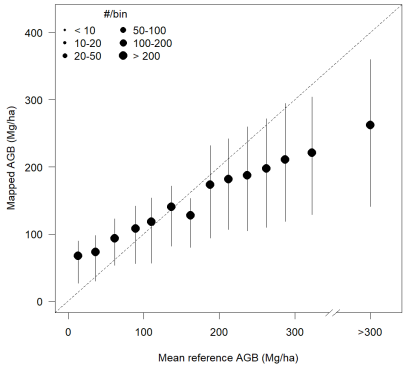
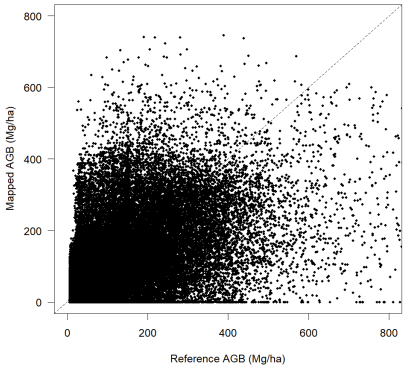
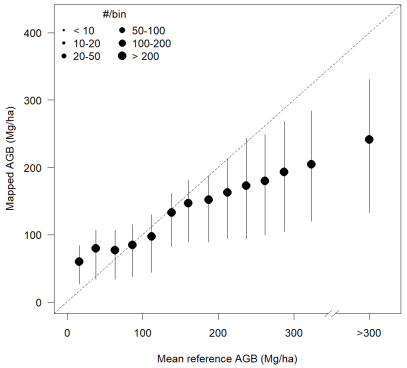




2016 v7





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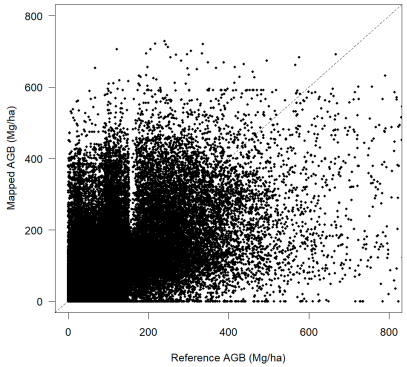

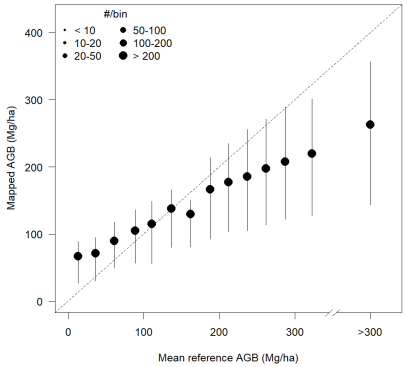

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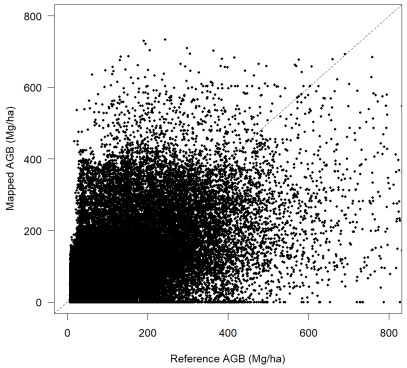

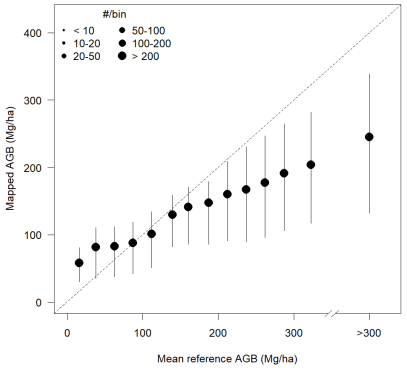

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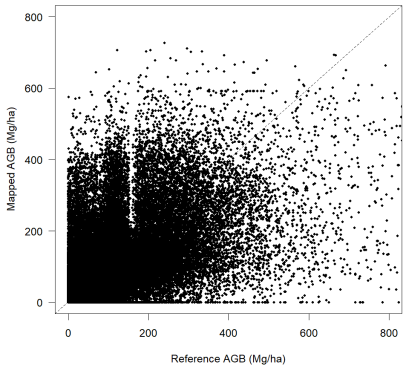
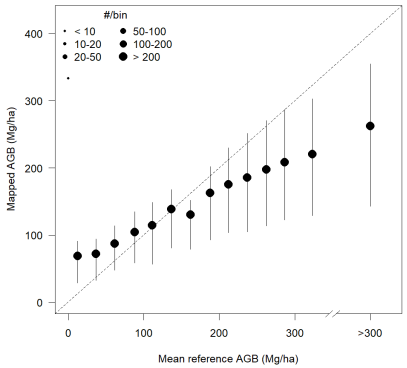
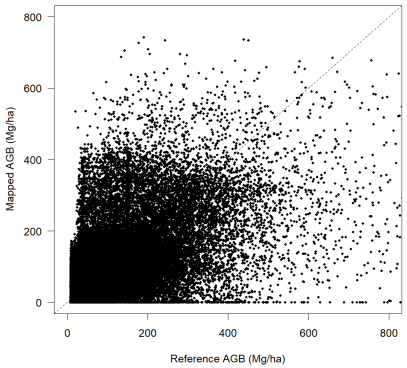
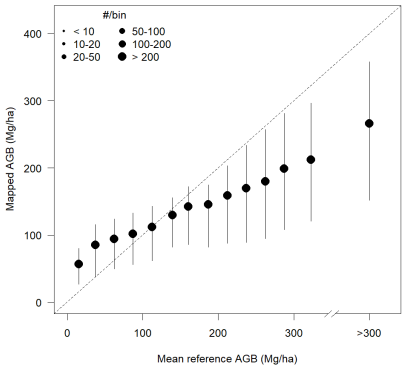


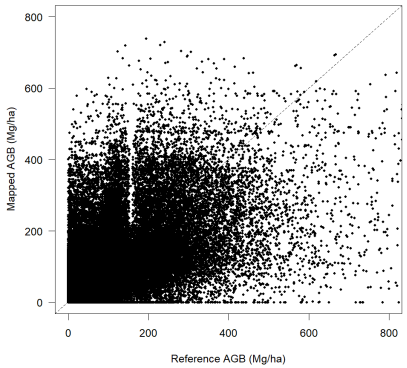


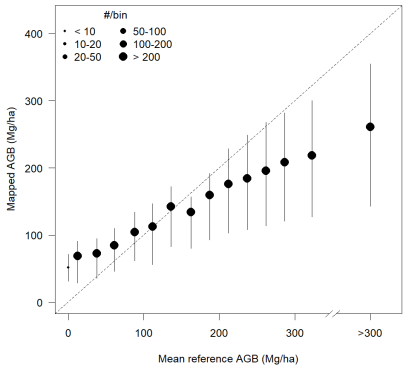
2018 v7



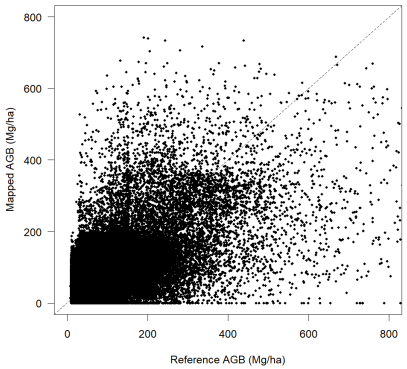


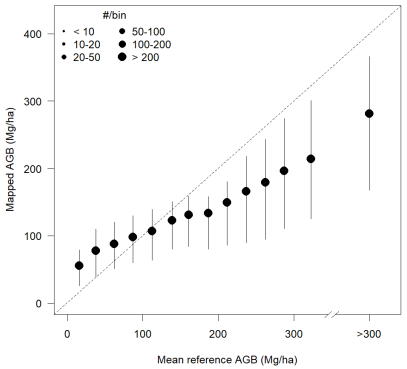
2008 v7



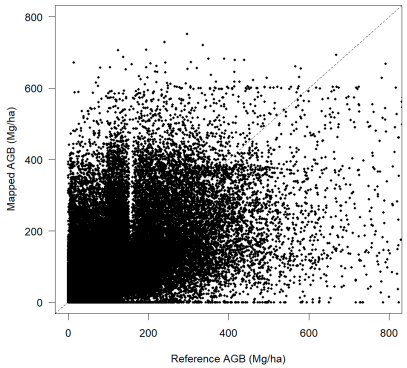


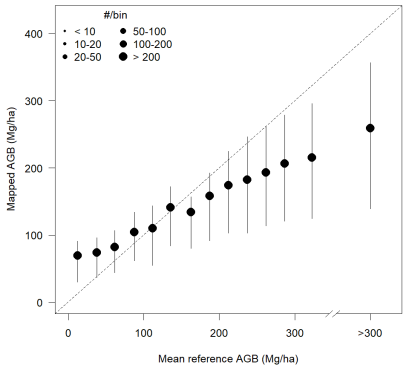
2019 v7



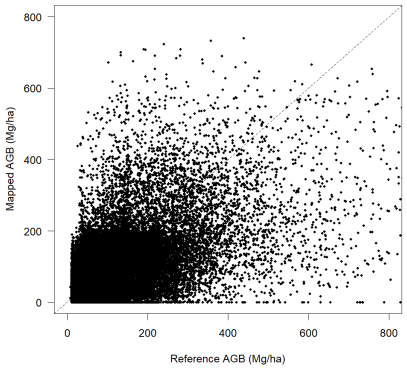


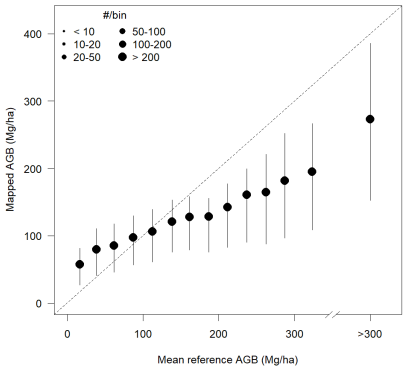
2009 v7



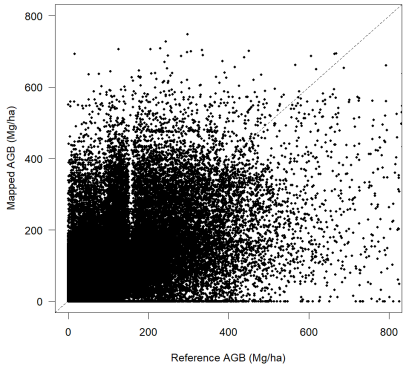


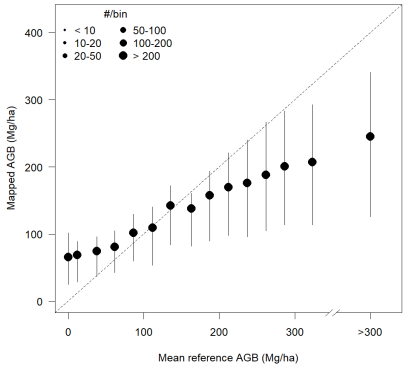
2020 v7



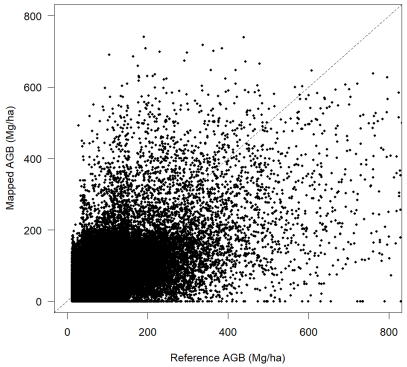


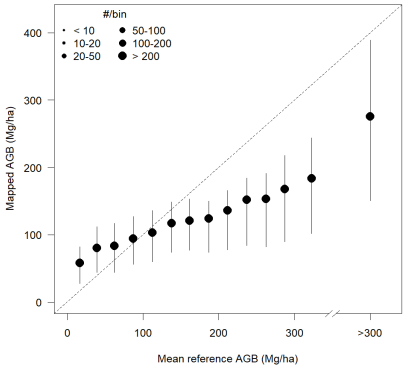
2010 v7



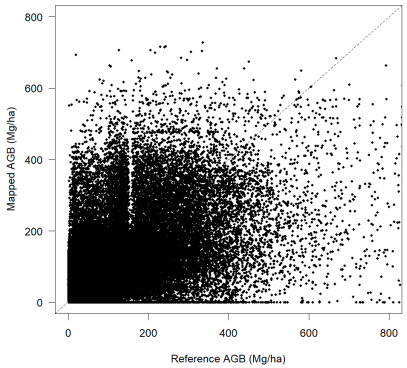


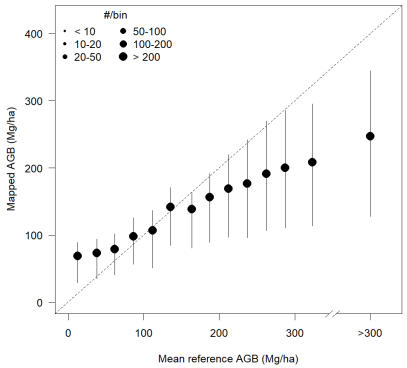
2021 v7



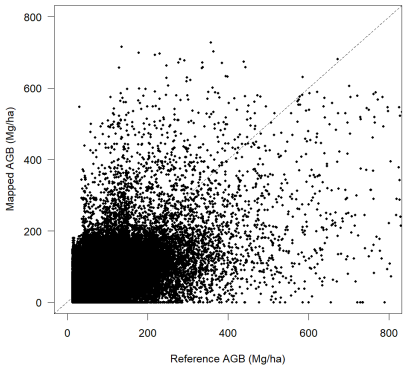


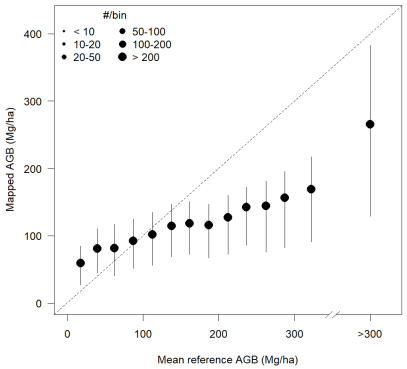
2011 v7



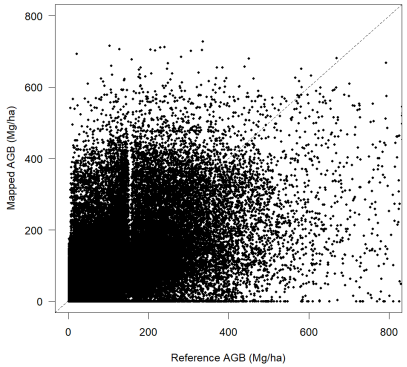


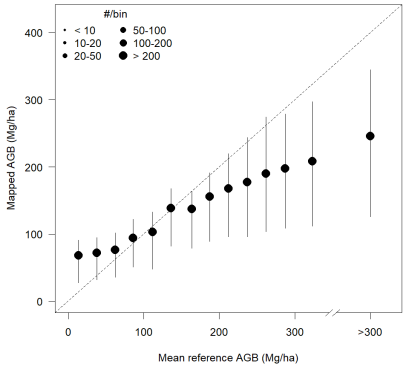
2022 v7



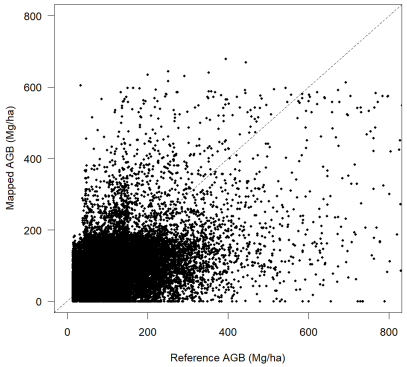


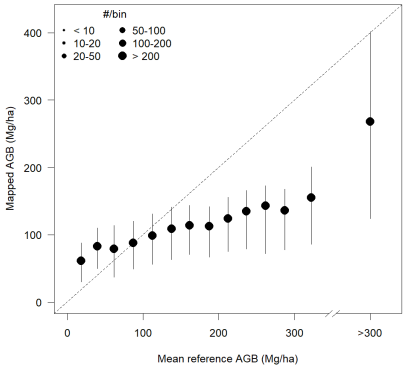
2012 v7





2023 v7





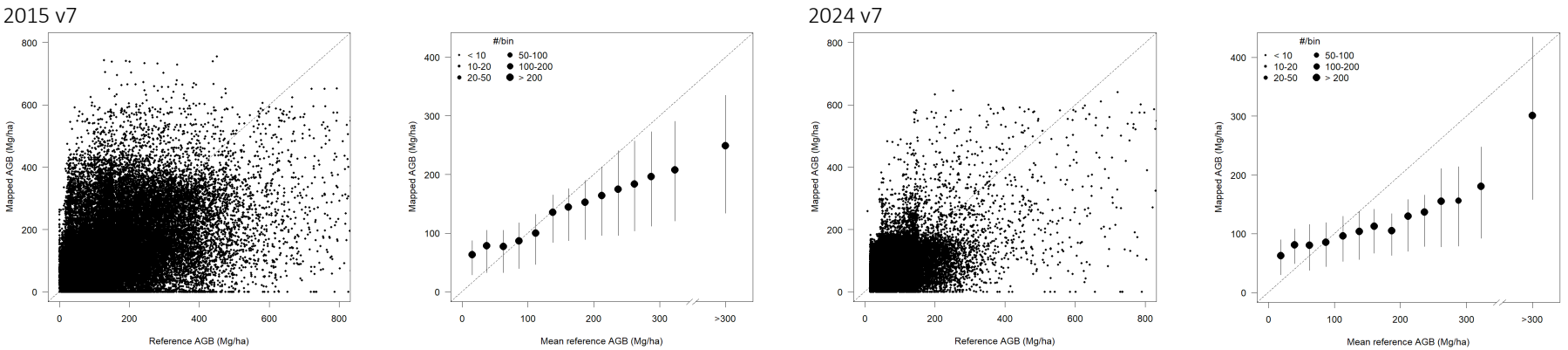


Figure 3. Plot-map comparisons for Tier 1 data at original resolution (i.e., without spatial aggregation) for the 18AGB maps; left column: scatterplots; right column: binned over 25 Mg/ha wide biomass ranges with whiskers representing the interquartile range of mapped biomass values. AGB_{ref} > 350 Mg/ha data are grouped into a single bin. Note the different scales on the left and right graphs for each year.

Table 3. Validation results per biomass range for Tier 1 data at original resolution for the 2005 map.

AGB_{ref} bin [Mg/ha]	# plots count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	MD [Mg/ha]	$RMSD$ [Mg/ha]	$Var(Plt)$ [a] [Mg/ha]^2	SE^2_{CCI} [a]	I_{Var}
0-50	30209	25	71	45	79	15331	1023	0
50-100	16257	75	101	26	78	18074	1593	0
100-150	11188	119	125	7	91	21519	2613	0
150-200	3495	177	153	-23	106	26657	3829	0
200-250	3495	223	184	-39	121	26614	5457	0
250-300	2413	273	204	-70	139	26002	6307	0
300-400	2523	343	225	-117	174	22251	8009	0
>400	2115	790	277	-513	866	59048	13491	1
total	71695	110	112	1	174	19913	2545	1

[a] simplified notation; referring to means over biomass ranges

Table 4. Validation results per biomass range for Tier 1 data at original resolution for the 2006 map.

AGB_{ref} bin [Mg/ha]	# plots count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	MD [Mg/ha]	$RMSD$ [Mg/ha]	$Var(Plt)$ [a] [Mg/ha]^2	SE^2_{CCI} [a]	I_{Var}
0-50	32684	25	69	44	76	14513	990	0
50-100	17710	74	97	23	73	16954	1450	0
100-150	12540	119	122	3	87	22567	2492	0
150-200	3930	177	151	-26	104	25756	3664	0
200-250	3696	223	181	-42	121	25019	5216	0
250-300	2525	273	202	-71	137	23541	6085	0
300-400	2629	343	225	-118	173	21642	7812	1
>400	2175	783	277	-506	856	56839	13044	1
total	77889	108	109	1	168	19146	2404	1

[a] simplified notation; referring to means over biomass ranges

Table 5. Validation results per biomass range for Tier 1 data at original resolution for the 2007 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)$ [a]	SE^2_{CCI} [a]	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	32752	25	70	45	77	14048	998	0
50-100	19116	73	94	22	70	16458	1343	0
100-150	13398	119	122	3	86	21395	2436	0
150-200	4335	177	149	-28	103	25137	3611	0
200-250	3809	223	180	-43	120	23943	5117	0
250-300	2566	273	202	-71	137	21643	6124	0
300-400	2655	342	224	-118	173	21624	7833	1
>400	2181	780	277	-503	854	57780	13256	1
total	80812	108	109	1	165	18568	2370	1

[a] simplified notation; referring to means over biomass ranges

Table 6. Validation results per biomass range for Tier 1 data at original resolution for the 2008 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)$ [a]	SE^2_{CCI} [a]	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	30900	25	71	46	76	14267	1002	0
50-100	20363	72	93	21	68	16036	1278	0
100-150	13717	119	122	3	85	20454	2445	0
150-200	4556	177	149	-28	103	24757	3658	0
200-250	3845	223	180	-43	121	22943	5038	0
250-300	2584	273	201	-72	137	20069	6286	0
300-400	2679	342	222	-120	174	21581	7859	1
>400	2197	779	276	-502	851	58265	13406	1
total	80841	110	109	0	165	18390	2391	1

[a] simplified notation; referring to means over biomass ranges

Table 7. Validation results per biomass range for Tier 1 data at original resolution for the 2009 map.

AGB_{ref} bin [Mg/ha]	# plots count	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)$ [a]	SE^2_{CCI} [a]	I_{Var}
		[Mg/ha]				[Mg/ha]^2		
0-50	29037	26	72	46	76	14570	1015	0
50-100	21472	71	91	19	66	15146	1266	0
100-150	14181	120	120	1	85	19440	2455	0
150-200	4812	177	148	-29	104	24421	3687	0
200-250	3849	223	178	-45	120	21857	5113	0
250-300	2609	273	199	-74	137	19576	6217	0
300-400	2703	343	221	-121	175	21568	7865	1
>400	2209	777	272	-505	853	57516	13767	1
total	80872	112	110	-2	165	18078	2433	1

[a] simplified notation; referring to means over biomass ranges

Table 8. Validation results per biomass range for Tier 1 data at original resolution for the 2010 map.

AGB_{ref} bin [Mg/ha]	# plots count	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)$[a]	SE^2_{CCI} [a]	I_{Var}
		[Mg/ha]				[Mg/ha]^2		
0-50	27103	25	72	46	77	14976	1014	0
50-100	21823	71	89	18	65	14562	1202	0
100-150	14647	120	121	1	86	18514	2410	0
150-200	5173	177	149	-28	104	23665	3521	0
200-250	4080	223	172	-51	124	20059	4745	0
250-300	2737	273	194	-79	142	18801	5845	0
300-400	2957	343	209	-135	187	20101	7156	1
>400	2352	758	262	-496	830	55830	12764	1
total	80872	116	110	-6	167	17822	2396	1

[a] simplified notation; referring to means over biomass ranges

Table 9. Validation results per biomass range for Tier 1 data at original resolution for the 2011 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	25222	26	71	45	76	15406	997	0
50-100	23215	71	86	15	64	13781	1148	0
100-150	14819	121	120	-1	86	17825	2400	0
150-200	5406	176	148	-28	104	23289	3575	0
200-250	4120	223	172	-51	124	19486	4757	0
250-300	2757	273	195	-78	142	18761	5828	0
300-400	2971	343	210	-133	187	20060	7215	1
>400	2362	757	264	-493	827	60195	12675	1
total	80872	118	110	-8	167	17711	2395	1

[a] simplified notation; referring to means over biomass ranges

Table 10. Validation results per biomass range for Tier 1 data at original resolution for the 2012 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	23355	27	70	43	75	15950	1032	0
50-100	24464	71	83	12	64	13068	1160	0
100-150	15149	122	118	-4	86	17314	2480	0
150-200	5614	176	147	-29	105	22974	3724	0
200-250	4145	223	172	-51	124	19236	4927	0
250-300	2786	273	194	-80	143	18808	5999	0
300-400	2988	344	210	-134	188	29734	7320	0
>400	2371	756	263	-493	826	50944	13200	1
total	80872	120	109	-11	167	17624	2489	1

[a] simplified notation; referring to means over biomass ranges

Table 11. Validation results per biomass range for Tier 1 data at original resolution for the 2015 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	19663	29	73	44	75	16624	1062	0
50-100	26150	73	81	8	64	12461	1088	0
100-150	15893	123	115	-8	80	16450	2216	0
150-200	6666	173	148	-25	100	21917	3482	0
200-250	4234	223	169	-54	122	19556	4520	0
250-300	2827	273	190	-84	140	18985	5489	0
300-400	3051	344	211	-133	181	19978	6852	1
>400	2388	754	266	-488	819	47130	11634	1
total	80872	126	110	-16	165	16943	2363	1

[a] simplified notation; referring to means over biomass ranges

Table 12. Validation results per biomass range for Tier 1 data at original resolution for the 2016 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	17794	30	73	43	73	17548	1061	0
50-100	26942	74	81	6	64	12186	1086	0
100-150	16332	123	112	-11	80	16082	2146	0
150-200	7153	171	149	-22	100	21766	3589	0
200-250	4290	223	167	-56	123	19543	4408	0
250-300	2864	273	186	-87	141	18958	5240	0
300-400	3076	343	206	-137	184	19937	6623	1
>400	2421	751	258	-493	822	46690	10613	1
total	80872	128	110	-19	167	16958	2335	1

[a] simplified notation; referring to means over biomass ranges

Table 13. Validation results per biomass range for Tier 1 data at original resolution for the 2017 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	15567	31	74	43	73	19054	1056	0
50-100	20648	75	85	11	67	15615	1118	0
100-150	14659	124	114	-10	78	18370	1927	0
150-200	6821	172	144	-28	98	22795	3014	0
200-250	4160	223	163	-60	123	20227	3948	0
250-300	2767	273	184	-90	145	19542	4923	0
300-400	2973	343	206	-137	185	20585	6325	1
>400	2348	757	264	-494	826	47968	10936	1

total	69943	136	114	-21	176	19385	2328	1

[a] simplified notation; referring to means over biomass ranges

Table 14. Validation results per biomass range for Tier 1 data at original resolution for the 2018 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	13092	31	77	46	76	18589	1106	0
50-100	14681	74	98	24	73	18160	1382	0
100-150	11949	125	121	-5	79	18920	2068	0
150-200	5718	172	144	-28	100	21508	3026	0
200-250	3350	223	164	-59	125	18058	4044	0
250-300	2084	273	188	-85	146	15473	5348	1
300-400	2190	343	220	-123	175	14588	7155	1
>400	1963	813	282	-531	893	46955	12301	1
total	55027	139	122	-17	191	19552	2568	1

[a] simplified notation; referring to means over biomass ranges

Table 15. Validation results per biomass range for Tier 1 data at original resolution for the 2019 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	10825	31	71	40	62	17949	889	0
50-100	12278	74	93	19	59	18227	1161	0
100-150	10297	126	115	-11	70	18828	1872	0
150-200	4688	172	132	-39	96	22022	2694	0
200-250	2673	222	156	-66	125	19684	3890	0
250-300	1639	273	187	-87	146	17534	5551	0
300-400	1679	343	227	-116	167	17141	7829	1
>400	1729	856	295	-561	942	51957	13377	1
total	45808	141	116	-24	200	19978	2435	1

[a] simplified notation; referring to means over biomass ranges

Table 16. Validation results per biomass range for Tier 1 data at original resolution for the 2020 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	9343	31	72	41	63	16970	902	0
50-100	11594	73	91	18	60	16750	1136	0
100-150	9851	126	114	-12	70	17797	1788	0
150-200	4157	172	128	-44	96	21661	2510	0
200-250	2509	222	150	-72	125	19947	3441	0

250-300	1416	273	172	-101	152	19299	4718	0
300-400	1356	342	208	-134	182	20783	6792	1
>400	1541	899	288	-611	995	57179	12919	1
total	41767	141	113	-28	208	19436	2252	1

[a] simplified notation; referring to means over biomass ranges

Table 17. Validation results per biomass range for Tier 1 data at original resolution for the 2021 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)$[a]	SE^2_{CCI}[a]	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	8006	32	73	41	62	15345	943	0
50-100	10612	74	89	15	57	15341	1132	0
100-150	9123	126	111	-15	69	16481	1754	0
150-200	3663	173	122	-51	96	20878	2279	0
200-250	2238	222	143	-80	127	20611	3170	0
250-300	1198	273	159	-114	158	20926	4321	0
300-400	1144	342	199	-143	190	22896	6661	1
>400	1320	910	293	-617	1011	58744	13316	1
total	37304	140	110	-30	207	18427	2182	1

[a] simplified notation; referring to means over biomass ranges

Table 18. Validation results per biomass range for Tier 1 data at original resolution for the 2022 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)$[a]	SE^2_{CCI}[a]	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	6838	32	73	41	62	13835	948	0
50-100	9718	73	87	13	56	13627	1070	0
100-150	8410	126	109	-17	71	14864	1668	0
150-200	3177	173	117	-56	95	19816	2000	0
200-250	1985	222	133	-89	126	21038	2634	0
250-300	1021	272	149	-123	164	21520	3591	1
300-400	884	341	182	-158	202	25960	5443	1
>400	920	964	287	-677	1094	63096	12459	1
total	32953	135	105	-30	200	16986	1894	1

[a] simplified notation; referring to means over biomass range

Table 19. Validation results per biomass range for Tier 1 data at original resolution for the 2023 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)$[a]	SE^2_{CCI}[a]	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	5448	32	75	44	62	11087	964	0
50-100	8910	73	83	10	54	11345	1026	0
100-150	7539	126	104	-22	68	12650	1546	0

150-200	2725	173	113	-60	95	18012	1861	0
200-250	1671	222	128	-93	125	20626	2347	0
250-300	814	272	141	-131	167	21192	3222	1
300-400	680	340	170	-170	207	26530	4776	1
>400	711	1018	291	-726	1145	67994	13454	1
total	28498	133	102	-31	198	14880	1771	1

[a] simplified notation; referring to means over biomass ranges

Table 20. Validation results per biomass range for Tier 1 data at original resolution for the 2024 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	4405	31	74	42	60	7059	880	0
50-100	7898	73	83	10	55	8315	985	0
100-150	6679	126	100	-26	69	9651	1418	0
150-200	1742	172	109	-62	95	11187	1922	0
200-250	888	222	132	-89	127	12024	2900	1
250-300	427	271	155	-116	161	12581	3918	1
300-400	313	339	200	-139	190	16800	6664	1
>400	442	993	315	-678	1121	65540	14062	1
total	22794	119	98	-21	173	10134	1624	1

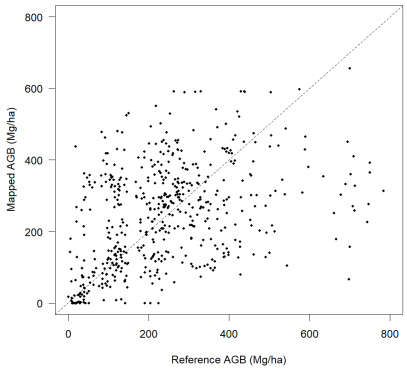
[a] simplified notation; referring to means over biomass ranges

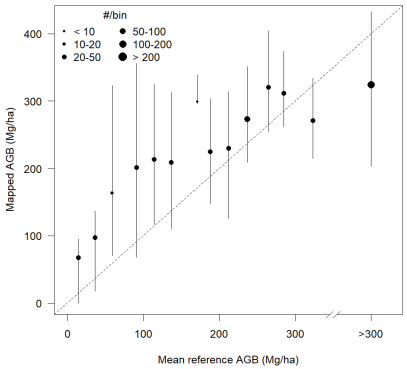
Tier 2 non-aggregated

Here, a better agreement between plot and map estimates is observed compared to the Tier 1 results, which can be attributed to the decreasing spatial mismatch between plots and map pixels. The binned ranges (right-hand side) show most biomass bins overlapping the 1:1 line except for 2005-2012 maps where overestimation seems more evident. This is influenced by certain reference data that have been excluded from 2016 onwards due to the temporal criteria.

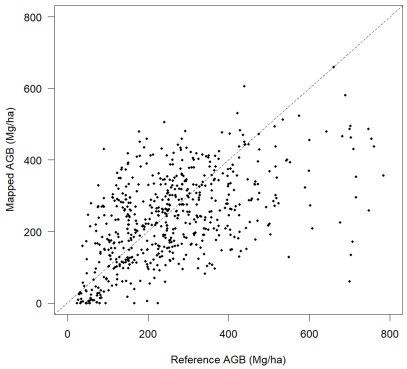
The results for 2015-2024 are very similar due to minimal changes in the biomass estimates from reference data used and maps. Note that the 2015-2024 comparisons also used less reference data than the rest of the comparisons (see Table 2). Most Tier 2 plots are located in the tropics (Figure 1).

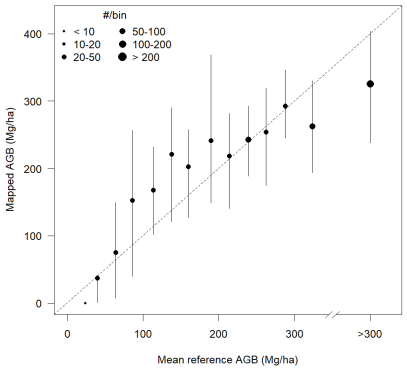
2005 v7



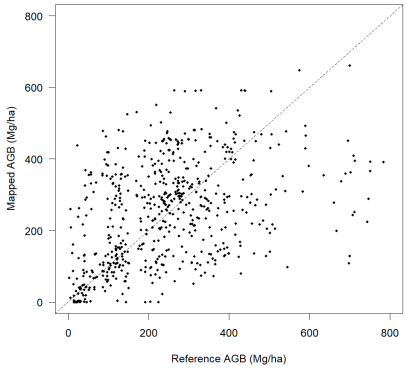


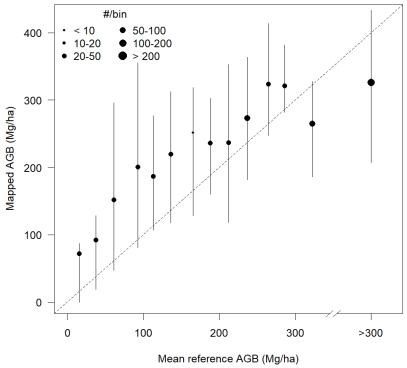
2016 v7



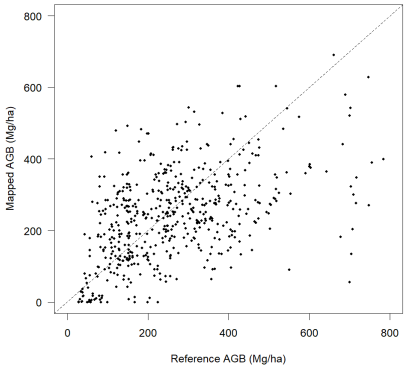


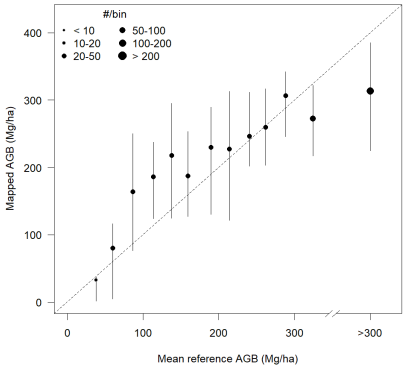
2006 v7



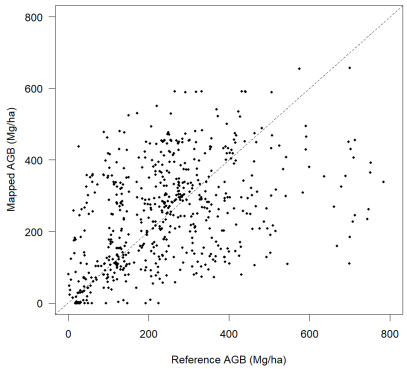


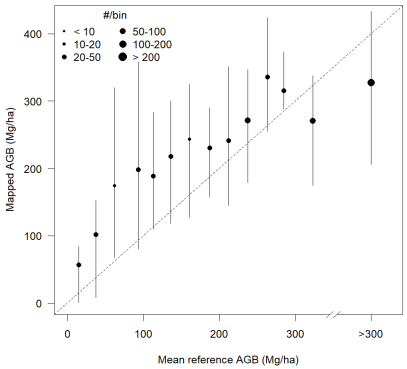
2017 v7



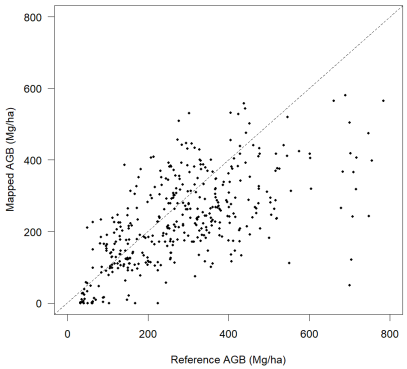


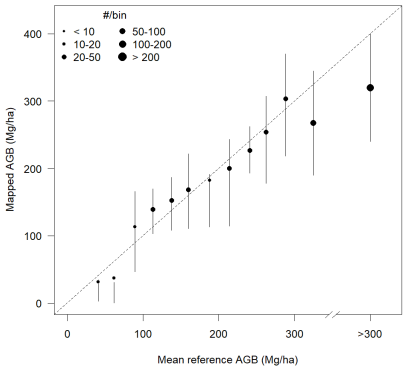
2007 v7



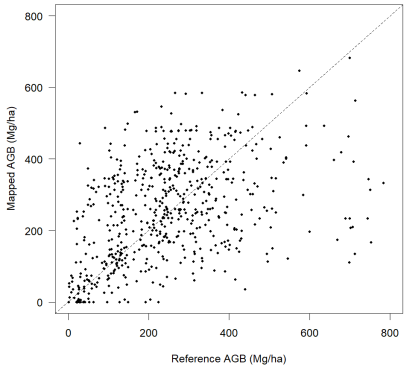


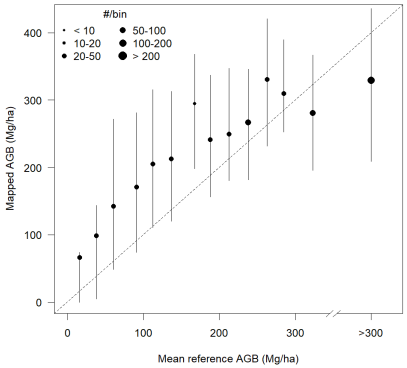
2018 v7



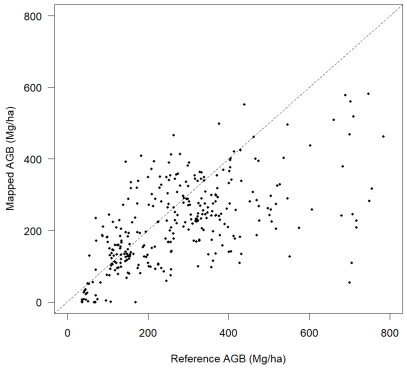


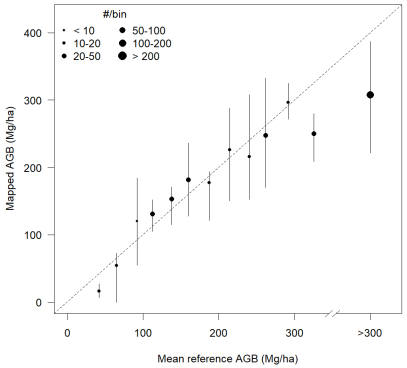
2008 v7



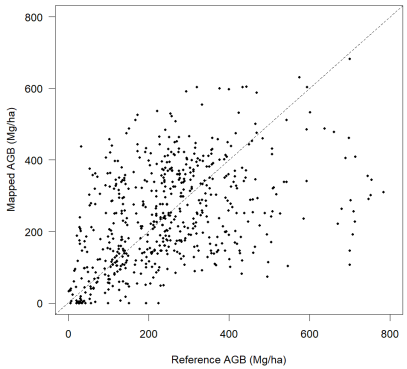


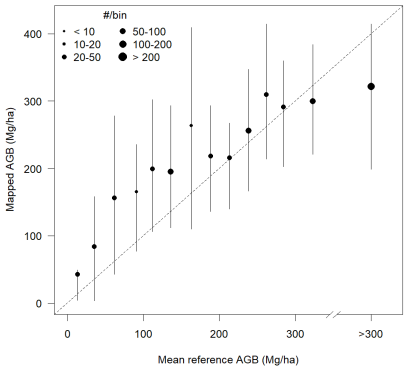
2019 v7



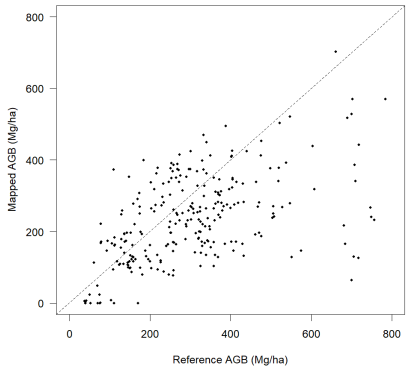


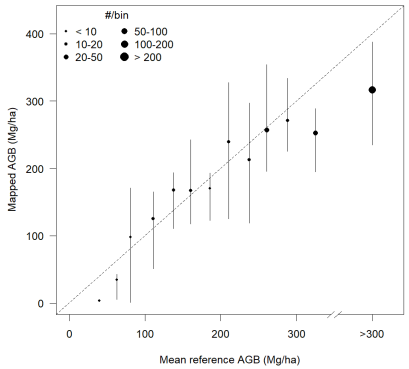
2009 v7



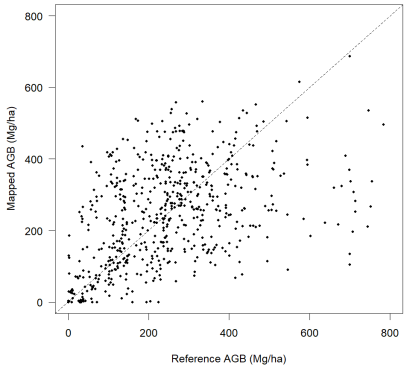


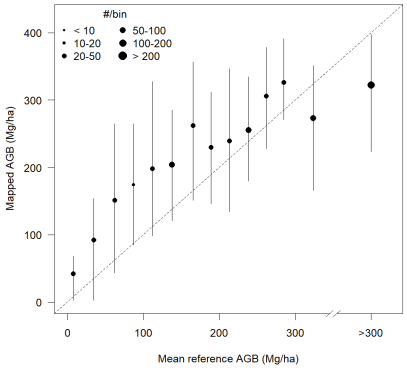
2020 v7



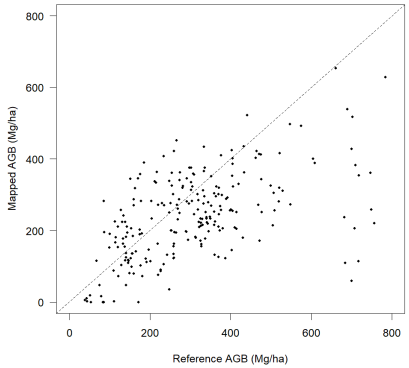


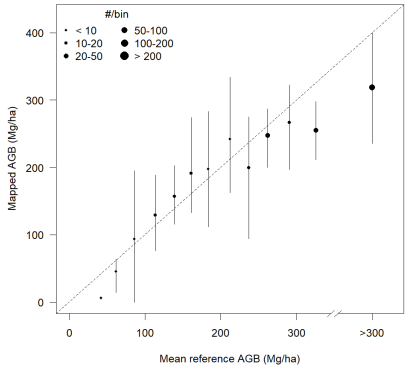
2010 v7



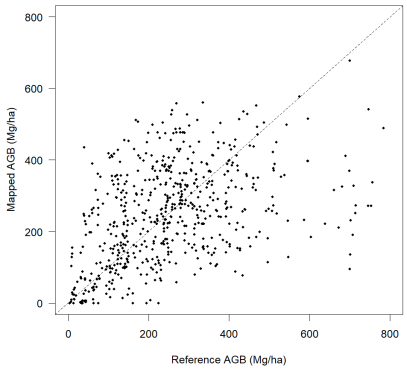


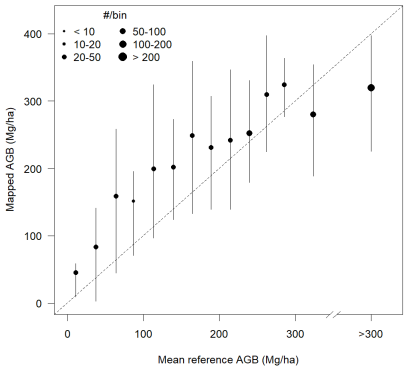
2021 v7



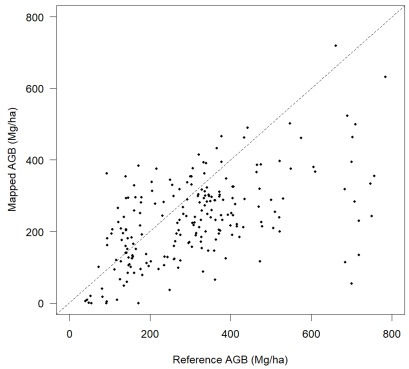


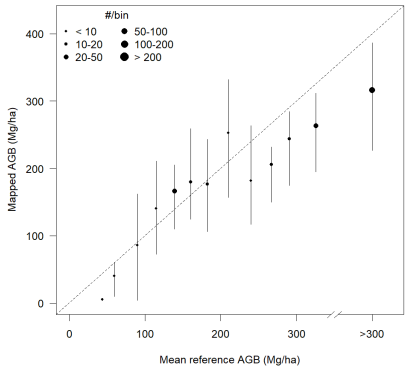
2011 v7



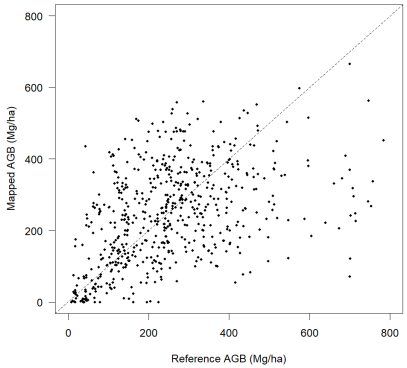


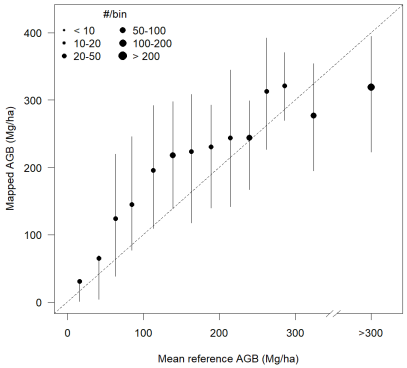
2022 v7



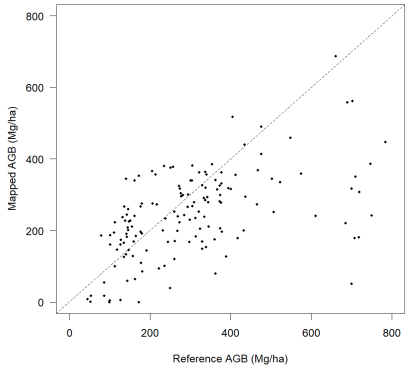


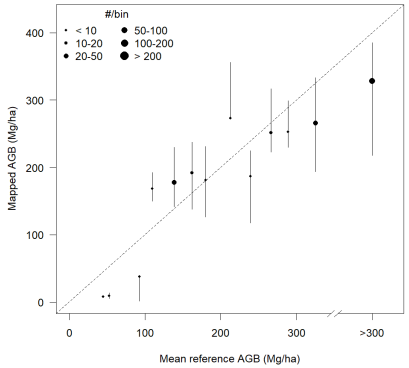
2012 v7





2023 v7





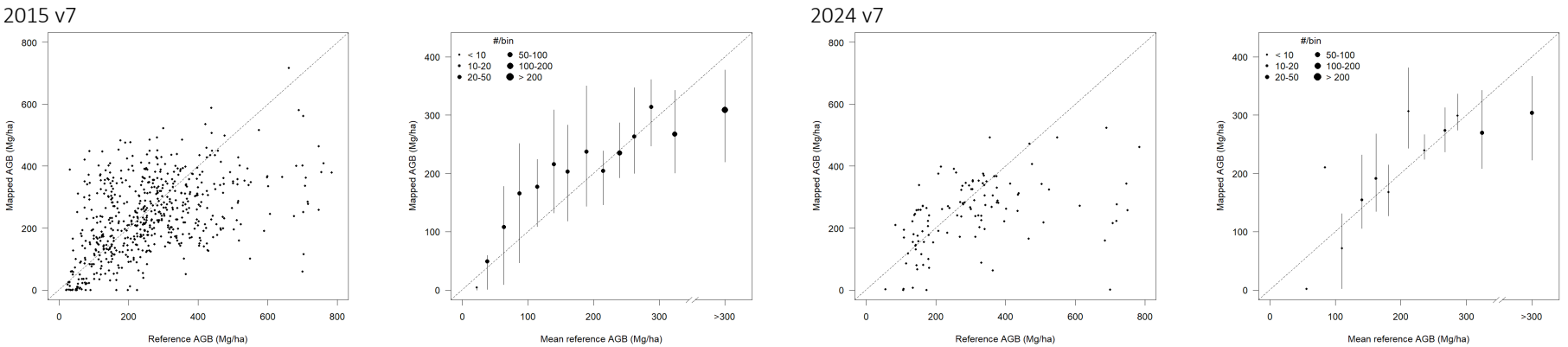


Figure 4. Plot-map comparisons for Tier 2 data at original resolution (i.e., without spatial aggregation); left column: scatterplots; right column: binned over 25 Mg/ha wide AGB ranges with whiskers representing the interquartile range of mapped AGB values and symbol size representing the number of plots per AGB range. AGB_{ref} > 350 Mg/ha data are grouped into a single bin. Note the different scales on the left and right graphs for each year.

Table 21. Validation results per biomass range for Tier 2 data at original resolution for the 2005 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	57	27	84	58	125	1117	3996	1
50-100	46	79	187	108	179	1315	13175	1
100-150	90	125	211	86	153	966	10461	1
150-200	31	185	237	52	120	1021	11136	1
200-250	96	227	255	29	123	2651	9988	1
250-300	61	272	318	45	115	2849	11258	0
300-400	86	348	268	-80	149	1399	12102	1
>400	91	638	350	-288	401	21201	19709	1
total	558	266	248	-18	206	4876	11829	1

[a] simplified notation; referring to means over biomass ranges

Table 22. Validation results per biomass range for Tier 2 data at original resolution for the 2006 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	63	29	85	56	118	1098	3715	1
50-100	50	79	179	100	172	1360	11891	1
100-150	93	125	204	79	143	898	9644	1
150-200	35	183	239	56	134	966	11254	1
200-250	101	227	259	31	132	2544	9846	1
250-300	80	273	323	50	117	2255	9759	1
300-400	108	345	267	-79	150	1417	10612	1
>400	102	618	352	-266	381	25154	18307	1
total	632	267	250	-17	199	5397	10930	1

[a] simplified notation; referring to means over biomass ranges

Table 23. Validation results per biomass range for Tier 2 data at original resolution for the 2007 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	67	28	84	55	116	1161	4119	1
50-100	41	79	187	108	180	973	13321	1
100-150	94	124	203	79	142	811	10736	1
150-200	38	180	234	54	132	904	10212	1
200-250	101	227	259	32	124	2462	9891	1
250-300	81	273	327	54	119	1232	10229	1
300-400	108	345	273	-72	146	1309	10342	1
>400	103	617	349	-268	382	40198	18270	1

total	633	268		-16	198	7675	11131	1

[a] simplified notation; referring to means over biomass ranges

Table 24. Validation results per biomass range for Tier 2 data at original resolution for the 2008 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^{2\ a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	61	27	83	56	117	1037	3726	1
50-100	42	75	156	81	147	885	10627	1
100-150	97	125	209	84	147	738	10382	1
150-200	40	181	259	77	151	819	10809	1
200-250	100	228	260	32	119	2410	9798	1
250-300	81	273	321	47	124	1138	10201	1
300-400	109	346	289	-57	132	1207	10347	1
>400	103	618	343	-274	389	23350	18250	1
total	633	269	254	-15	198	4857	10943	1

[a] simplified notation; referring to means over biomass ranges

Table 25. Validation results per biomass range for Tier 2 data at original resolution for the 2009 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^{2\ a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	56	27	70	42	94	1084	2921	1
50-100	44	74	160	86	153	805	9822	1
100-150	95	125	197	72	136	668	10198	1
150-200	46	179	236	57	152	764	11111	1
200-250	98	228	240	12	108	2385	9684	0
250-300	82	273	300	27	116	1053	10377	1
300-400	109	346	298	-48	130	1122	10521	1
>400	104	616	334	-282	383	22798	19026	1
total	634	270	246	-25	193	4745	11043	1

[a] simplified notation; referring to means over biomass ranges

Table 26. Validation results per biomass range for Tier 2 data at original resolution for the 2010 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	52	23	70	48	104	948	2816	1
50-100	42	71	160	89	149	686	8520	1
100-150	99	125	201	76	138	623	10038	1
150-200	47	179	244	65	150	727	10737	1
200-250	97	229	249	20	117	2347	9515	1
250-300	83	274	316	43	118	984	10564	1
300-400	108	346	279	-67	126	1046	10598	1
>400	106	613	338	-275	379	8765	18571	1
total	634	272	249	-22	194	2406	10908	1

[a] simplified notation; referring to means over biomass ranges

Table 27. Validation results per biomass range for Tier 2 data at original resolution for the 2011 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	50	27	67	41	96	834	2866	1
50-100	44	73	156	82	142	595	7662	1
100-150	96	127	201	74	133	581	9751	1
150-200	50	178	239	61	150	675	10543	1
200-250	96	229	248	19	115	2323	9515	1
250-300	84	274	317	43	117	929	10322	1
300-400	106	346	284	-62	126	989	10142	1
>400	108	610	333	-276	383	8586	17975	1
total	634	273	249	-24	195	2351	10632	1

[a] simplified notation; referring to means over biomass ranges

Table 28. Validation results per biomass range for Tier 2 data at original resolution for the 2012 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	48	31	51	20	85	663	3240	1
50-100	43	74	134	60	118	611	6829	1
100-150	94	127	208	81	134	538	10905	1
150-200	54	177	227	51	146	646	10456	1
200-250	95	230	244	14	114	2314	9585	1
250-300	85	274	317	43	118	883	10454	1
300-400	107	346	285	-61	124	939	10040	1
>400	108	610	330	-281	390	8561	18100	1

total	634	275	246	-28	196	2308	10831	1

[a] simplified notation; referring to means over biomass ranges

Table 29. Validation results per biomass range for Tier 2 data at original resolution for the 2015 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	28	35	43	7	79	558	1127	1
50-100	57	74	134	60	136	520	6551	1
100-150	82	127	197	70	126	493	9381	1
150-200	69	172	217	45	123	570	10030	1
200-250	89	229	222	-7	94	2371	9881	0
250-300	90	274	287	13	91	828	9439	0
300-400	107	346	272	-74	113	879	9951	1
>400	112	605	322	-283	378	8249	16490	1
total	634	280	238	-42	188	2253	10263	1

[a] simplified notation; referring to means over biomass ranges

Table 30. Validation results per biomass range for Tier 2 data at original resolution for the 2016 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	25	38	34	-4	47	592	801	1
50-100	57	76	117	41	114	529	5578	1
100-150	78	126	196	69	118	496	7940	1
150-200	75	170	216	46	118	563	9991	1
200-250	89	230	233	4	91	2378	9525	0
250-300	89	274	272	-2	90	832	9109	0
300-400	107	345	275	-70	115	888	10002	1
>400	114	602	339	-263	368	8121	15771	1
total	634	281	240	-41	183	2259	9832	1

[a] simplified notation; referring to means over biomass ranges

Table 31. Validation results per biomass range for Tier 2 data at original resolution for the 2017 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	17	38	33	-5	44	451	264	1
50-100	53	76	129	53	128	674	5007	1
100-150	73	128	205	77	123	520	8794	1
150-200	71	170	202	32	109	546	8943	1
200-250	74	230	239	9	104	2696	10495	0
250-300	73	273	280	7	95	806	10162	0

300-400	99	345	267	-79	127	906	9899	1
>400	110	603	334	-269	376	8359	16023	1
total	570	287	242	-45	194	2435	10189	1

[a] simplified notation; referring to means over biomass ranges

Table 32. Validation results per biomass range for Tier 2 data at original resolution for the 2018 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	16	41	32	-9	48	478	270	1
50-100	32	77	78	1	73	883	1854	1
100-150	47	126	146	20	68	595	2759	1
150-200	39	169	173	4	87	598	2883	1
200-250	45	229	215	-14	91	4015	4092	1
250-300	60	272	273	1	94	878	7258	1
300-400	93	345	267	-77	119	954	9053	1
>400	104	607	340	-267	373	8784	14865	1
total	436	315	236	-79	200	3034	7599	1

[a] simplified notation; referring to means over biomass ranges

Table 33. Validation results per biomass range for Tier 2 data at original resolution for the 2019 map

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD\ Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------			[Mg/ha]^2		
0-50	10	42	17	-25	27	509	67	1
50-100	24	75	79	4	77	961	2259	1
100-150	50	126	143	17	62	669	3021	1
150-200	33	170	180	10	92	600	2661	1
200-250	33	227	221	-6	99	3822	4991	1
250-300	44	271	263	-8	84	1910	5778	0
300-400	75	344	250	-93	119	969	8267	1
>400	78	656	330	-326	428	11369	14642	1
total	347	318	226	-92	219	3605	7132	1

[a] simplified notation; referring to means over biomass ranges

Table 34. Validation results per biomass range for Tier 2 data at original resolution for the 2020 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD$	$Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	4	40	4	-36	36	586	3	1
50-100	15	74	73	-1	75	1190	1530	1
100-150	29	128	152	24	85	871	3659	1
150-200	27	169	168	-1	83	623	2666	1
200-250	24	225	225	0	101	752	4560	1
250-300	43	268	261	-7	86	2995	5720	0
300-400	75	343	257	-85	121	1026	8174	1
>400	75	666	336	-330	426	11787	14615	1
total	292	350	244	-106	232	4007	7759	1

[a] simplified notation; referring to means over biomass ranges

Table 35. Validation results per biomass range for Tier 2 data at original resolution for the 2021 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD$	$Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	3	42	6	-36	36	636	3	1
50-100	13	78	79	0	90	1518	1632	1
100-150	29	130	147	17	69	964	3037	1
150-200	25	169	194	24	106	676	3249	1
200-250	19	225	220	-6	114	868	4323	1
250-300	39	269	252	-17	81	3313	4636	0
300-400	69	343	257	-86	113	1130	7994	1
>400	70	675	341	-334	444	12566	15317	1
total	267	355	246	-109	243	4381	7780	1

[a] simplified notation; referring to means over biomass ranges

Table 36. Validation results per biomass range for Tier 2 data at original resolution for the 2022 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	$RMSD$	$Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{var}
[Mg/ha]	count	[Mg/ha]				[Mg/ha]^2		
0-50	3	44	5	-38	39	679	2	1
50-100	12	82	74	-8	103	1880	1720	1
100-150	30	133	160	27	87	1121	3422	1
150-200	23	170	178	8	95	666	2665	1
200-250	13	226	215	-12	118	911	4923	1
250-300	26	276	220	-56	88	1327	5237	1
300-400	68	344	264	-80	118	1263	8428	1
>400	67	686	337	-349	448	13117	15190	1

total	242	366	243	-123	252	4482	8164	1

[a] simplified notation; referring to means over biomass ranges

Table 37. Validation results per biomass range for Tier 2 data at original resolution for the 2023 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	SE^2_{CCI} [a]	I_{var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	1	45	8	-37	37	515	4	1
50-100	9	84	32	-52	81	1938	1278	1
100-150	26	132	176	44	85	1513	3636	1
150-200	17	169	187	18	95	735	3026	1
200-250	11	227	226	-1	121	1017	4973	1
250-300	22	276	252	-24	74	1549	5377	0
300-400	43	343	268	-75	110	1591	9184	1
>400	44	701	349	-352	447	13952	15159	1
total	173	354	248	-106	240	4609	8049	1

[a] simplified notation; referring to means over biomass ranges

Table 38. Validation results per biomass range for Tier 2 data at original resolution for the 2024 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	SE^2_{CCI} [a]	I_{var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	2	70	106	36	97	1483	1984	1
100-150	23	130	126	-5	82	2273	3242	1
150-200	18	169	182	13	89	906	3141	1
200-250	7	222	278	56	99	1096	6354	1
250-300	18	276	285	9	59	1748	4788	0
300-400	38	339	280	-59	104	1757	9712	0
>400	33	686	304	-381	467	13147	11761	1
total	139	347	246	-101	241	4398	7359	1

[a] simplified notation; referring to means over biomass ranges

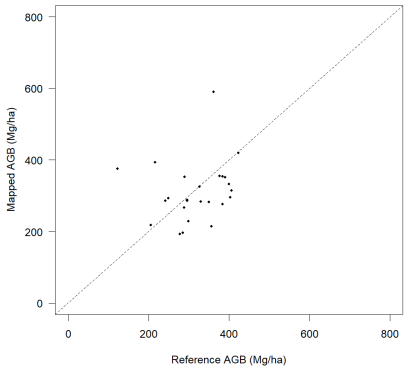
In most cases, the indicator variable I_{Var} = 1, indicating the CCI Biomass maps are *optimistic* about map precision.

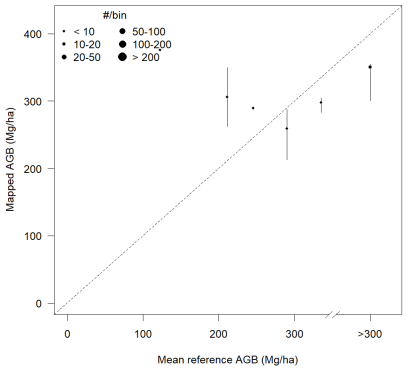
Tier 3 non-aggregated

The non-aggregated results (i.e., at original plot level) of global plot-map comparisons using Tier 3 data (plot size ≥ 6 ha) are shown in Figure 5 and Tables 39-57. Similar to Tier 2, spatial aggregation to 0.1° cells was omitted because of the small number of available Tier 3 plots.

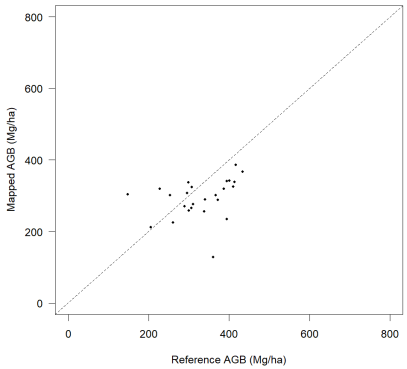
It is important to note that most Tier 3 plots are in the tropics and cover an AGB range of between 150 and 450 Mg/ha (i.e., the AGB range where the maximum AGB parameter of the AGB retrieval algorithm needs revision), and so lack low AGB densities. The small number of plots and the large scatter hardly allow conclusions to be drawn based on these data, except for the general trend of the map to under-predict AGB in the higher part of the assessed AGB range, which was also observed with the Tier 1 & 2 data. Note that 2015-2024 comparisons used fewer reference data.

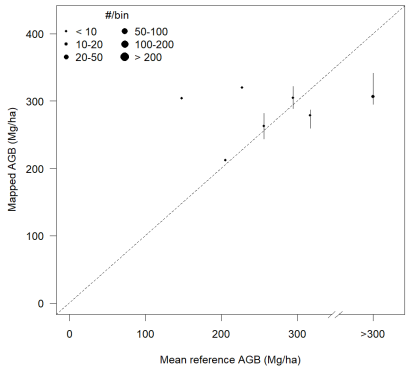
2005 v7



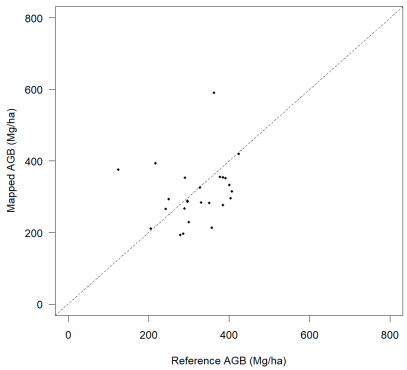


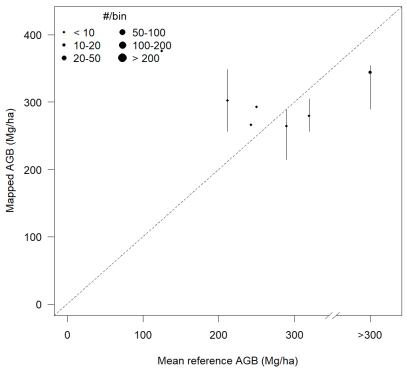
2016 v7



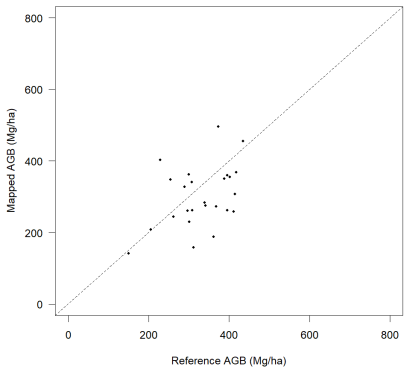


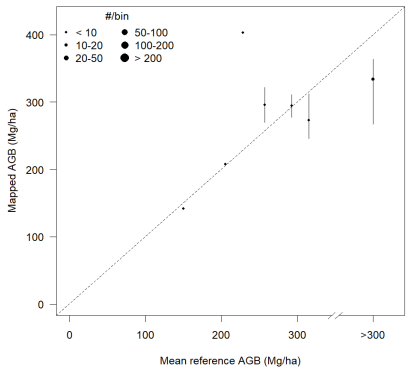
2006 v7



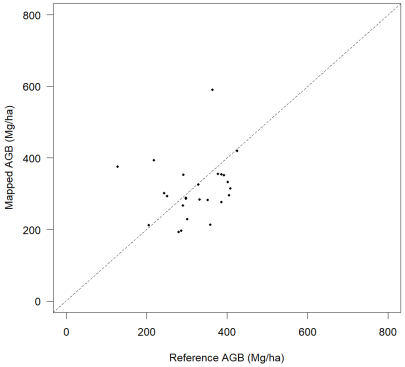


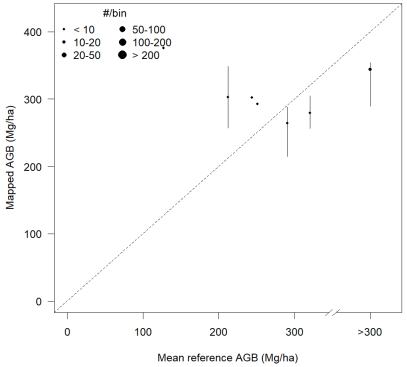
2017 v7



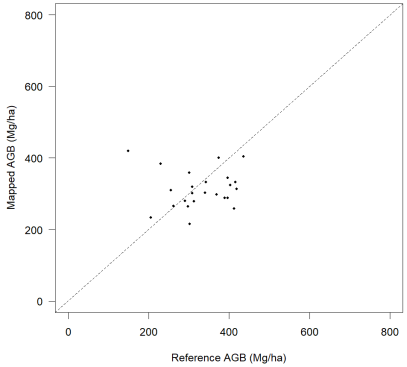


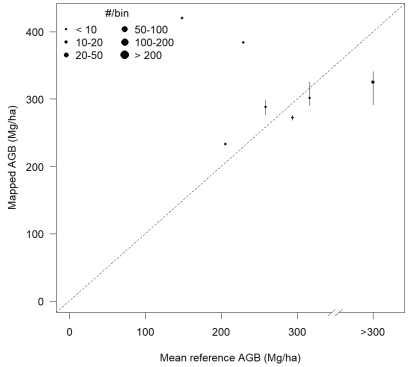
2007 v7



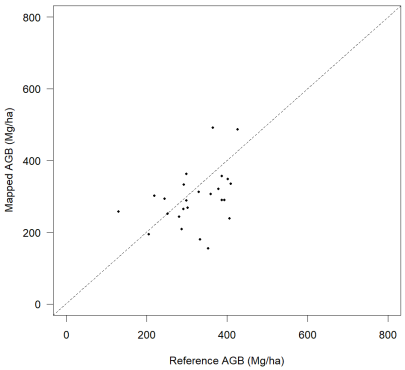


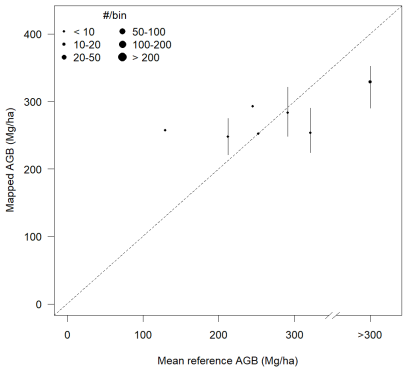
2018 v7



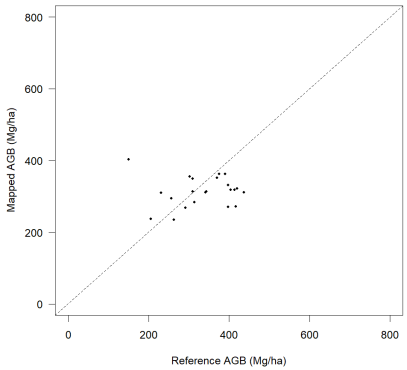


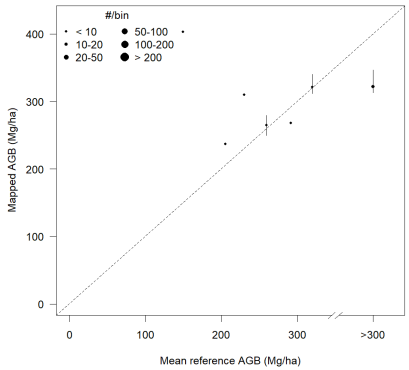
2008 v7



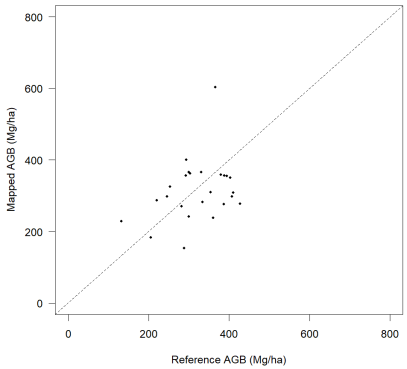


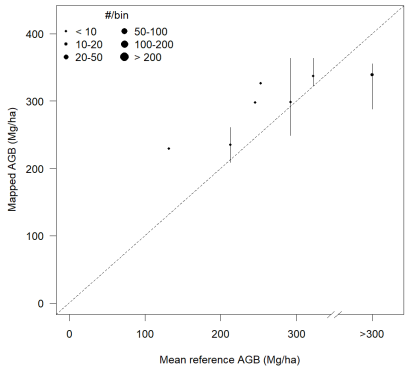
2019 v7



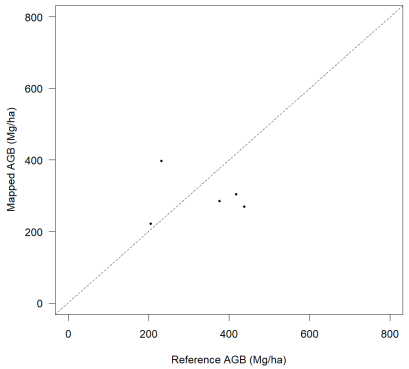


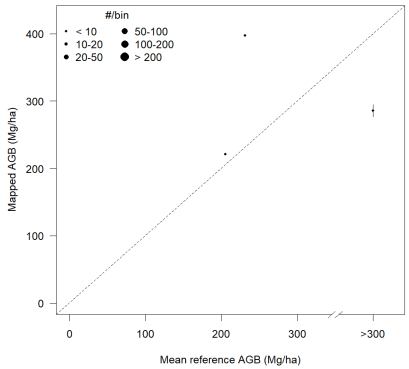
2009 v7



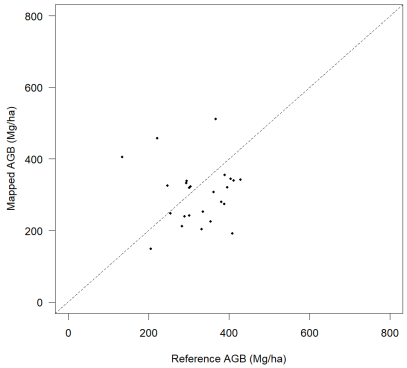


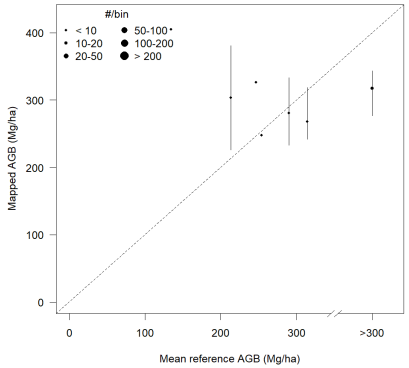
2020 v7



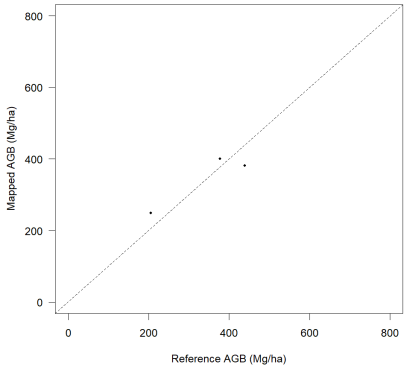


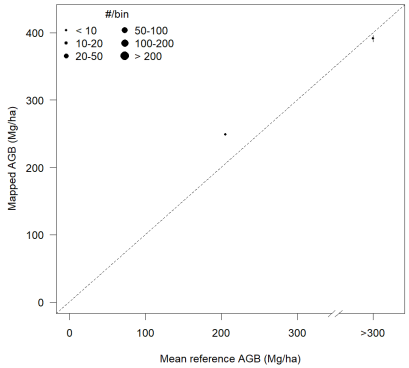
2010 v7



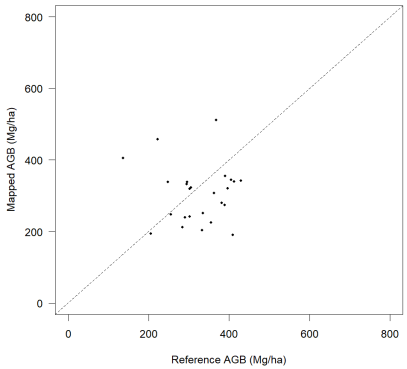


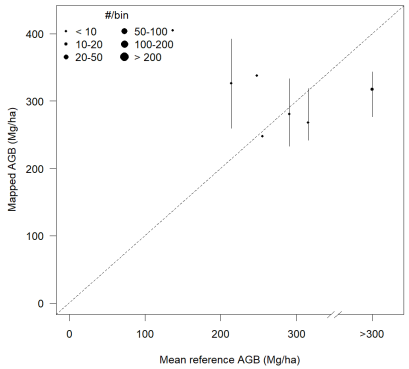
2021 v7



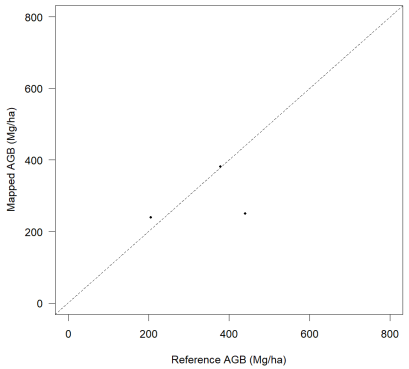


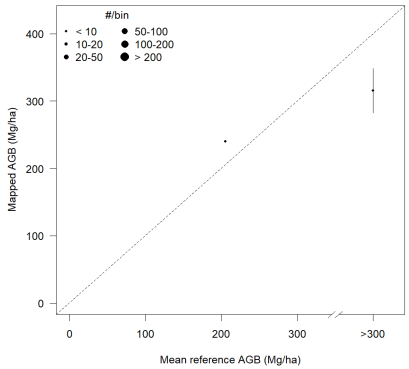
2011 v7



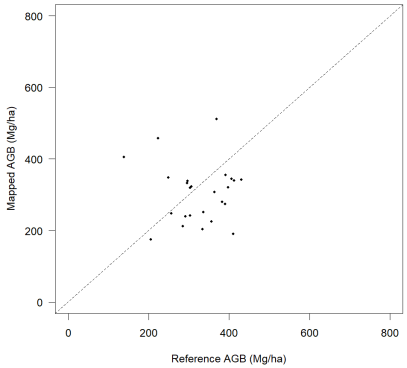


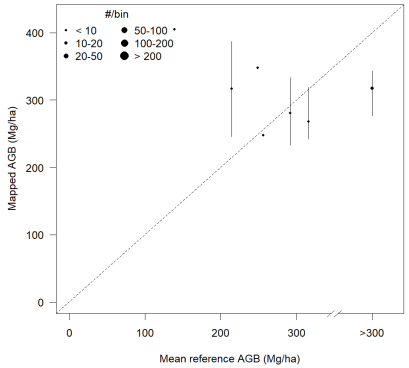
2022 v7



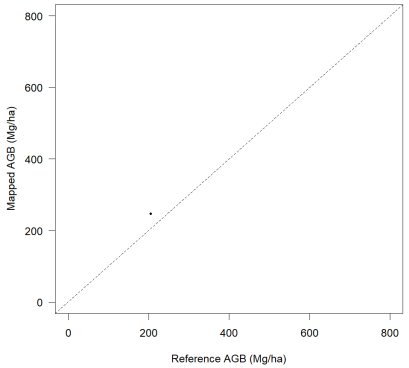


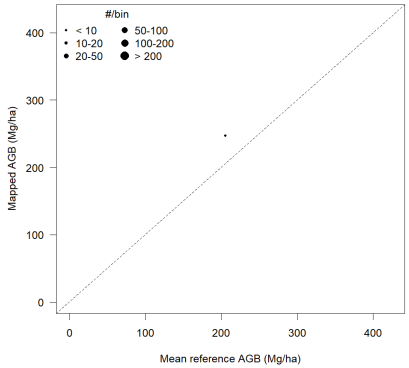
2012 v7





2023 v7





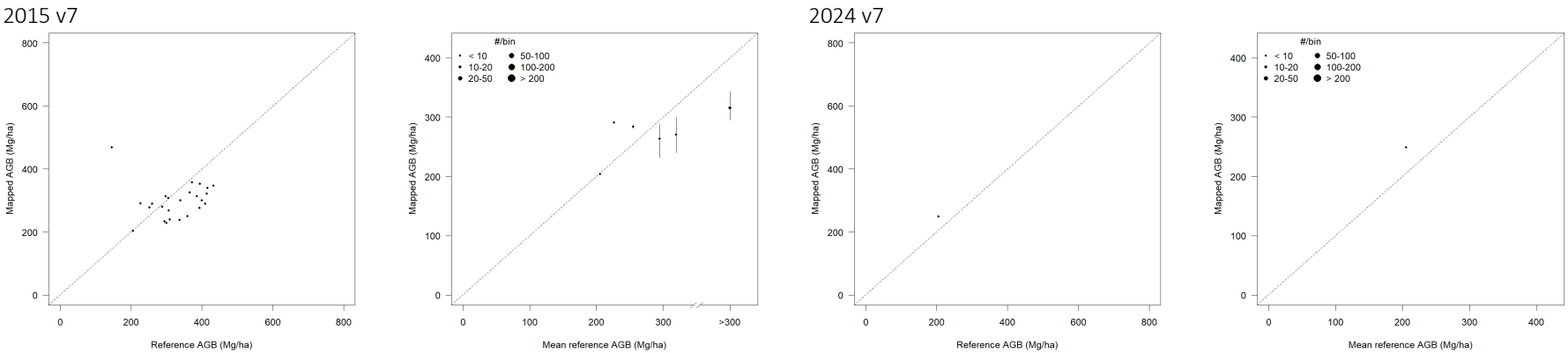


Figure 5. Plot-map comparisons for Tier 3 data at original resolution (i.e., without spatial aggregation); left column: scatterplots; right column: binned over 25 Mg/ha wide AGB ranges with whiskers representing the interquartile range of mapped AGB

Table 39. Validation results per biomass range for Tier 3 data at the original resolution for the 2005 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	123	376	253	253	274	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	4	228	298	70	94	6549	8816	0
250-300	7	290	259	-31	59	847	12744	0
300-400	10	365	337	-29	99	789	14847	0
>400	3	410	344	-67	81	775	17313	0
total	25	318	311	-7	98	1704	13746	0

[a] simplified notation; referring to means over the biomass ranges

Table 40. Validation results per biomass range for Tier 3 data at the original resolution for the 2006 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	125	376	251	251	251	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	3	222	290	68	103	7023	6614	0
250-300	7	284	268	-15	56	770	12709	0
300-400	10	356	326	-30	99	709	14900	0
>400	4	409	341	-68	79	690	16407	0
total	25	319	310	-9	98	1463	13688	0

[a] simplified notation; referring to means over the biomass ranges

Table 41. Validation results per biomass range for Tier 3 data at the original resolution for the 2007 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	127	376	249	249	230	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	3	223	303	80	107	5703	6582	0

250-300	7	285	268	-16	56	702	12780	0
300-400	10	357	326	-31	100	641	15040	0
>400	4	410	341	-69	79	622	16407	0
total	25	320	312	-9	98	1246	13760	0

[a] simplified notation; referring to means over the biomass ranges

Table 42. Validation results per biomass range for Tier 3 data at the original resolution for the 2008 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				$[Mg/ha]^2$		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	130	257	127	127	212	18769	0
150-200	-	-	-	-	-	-	-	-
200-250	3	223	263	40	56	4538	8038	0
250-300	7	286	279	-7	45	642	12843	0
300-400	10	358	297	-61	103	581	15239	0
>400	4	411	352	-59	100	562	16598	0
total	25	321	295	-26	86	1055	14063	0

[a] simplified notation; referring to means over the biomass ranges

Table 43. Validation results per biomass range for Tier 3 data at the original resolution for the 2009 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				$[Mg/ha]^2$		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	132	229	97	97	197	18769	0
150-200	-	-	-	-	-	-	-	-
200-250	3	224	256	32	51	3528	6814	0
250-300	7	287	302	15	82	590	12878	0
300-400	10	359	351	-9	98	529	15216	0
>400	4	412	309	-103	108	510	16737	0
total	25	322	314	-8	91	890	13939	0

[a] simplified notation; referring to means over the biomass ranges

Table 44. Validation results per biomass range for Tier 3 data at the original resolution for the 2010 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100								
100-150	1	134	405	271	271	183	19044	1
150-200	-	-	-	-	-	-	-	-
200-250	3	225	311	86	148	2674	8004	1
250-300	5	283	274	-9	47	602	11650	0
300-400	12	350	301	-49	90	472	14966	0
>400	4	413	305	-108	125	466	16577	0
total	25	323	302	-21	111	750	13888	0

[a] simplified notation; referring to means over the biomass ranges

Table 45. Validation results per biomass range for Tier 3 data at the original resolution for the 2011 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100								
100-150	1	136	405	269	269	172	19044	1
150-200	-	-	-	-	-	-	-	-
200-250	3	225	330	105	146	1975	8751	1
250-300	5	284	274	-10	47	566	11748	0
300-400	12	351	301	-50	91	436	15088	0
>400	4	414	304	-109	126	430	16577	0
total	25	324	304	-20	111	635	14056	0

[a] simplified notation; referring to means over the biomass ranges

Table 46. Validation results per biomass range for Tier 3 data at the original resolution for the 2012 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100								
100-150	1	139	405	266	266	164	19044	1
150-200	-	-	-	-	-	-	-	-
200-250	3	226	327	101	148	756	9274	1
250-300	5	285	274	-11	47	538	11650	0

300-400	12	352	301	-51	91	408	14966	0
>400	4	415	304	-110	127	402	16514	0
total	25	325	303	-22	112	465	14031	0

[a] simplified notation; referring to means over the biomass ranges

Table 47. Validation results per biomass range for Tier 3 data at the original resolution for the 2015 map. (No updated data)

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	146	469	323	323	153	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	2	216	248	32	46	946	5044	0
250-300	6	282	270	-11	42	469	11743	0
300-400	12	355	294	-61	72	372	14917	0
>400	4	418	325	-93	94	366	16434	0
total	25	328	297	-32	93	432	13762	0

[a] simplified notation; referring to means over the biomass ranges

Table 48. Validation results per biomass range for Tier 3 data at the original resolution for the 2016 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	148	304	156	156	154	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	2	216	266	50	66	948	5188	0
250-300	5	279	288	9	33	407	11008	0
300-400	12	348	274	-74	96	414	12804	0
>400	5	415	352	-63	66	365	14249	0
total	25	329	293	-36	83	435	12363	0

[a] simplified notation; referring to means over the biomass ranges

Table 49. Validation results per biomass range for Tier 3 data at the original resolution for the 2017 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-

150-200	1	150	142	-8	8	158	18496	0
200-250	2	217	306	89	124	954	5238	1
250-300	4	275	295	20	55	444	13334	0
300-400	13	345	296	-50	95	418	14220	0
>400	5	416	349	-67	90	377	16089	0
total	25	330	301	-29	89	446	13905	0

[a] simplified notation; referring to means over the biomass ranges

Table 50. Validation results per biomass range for Tier 3 data at the original resolution for the 2018 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	149	420	271	271	164	18769	1
150-200	-	-	-	-	-	-	-	-
200-250	2	217	308	91	111	964	5314	1
250-300	4	276	280	4	33	464	12367	0
300-400	12	345	311	-34	60	396	14282	0
>400	5	417	326	-91	99	397	15296	0
total	24	330	313	-16	90	445	13614	0

[a] simplified notation; referring to means over the biomass ranges

Table 51. Validation results per biomass range for Tier 3 data at the original resolution for the 2019 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE_{CCI}^{2\,a}$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	1	150	403	253	253	172	18496	1
150-200	-	-	-	-	-	-	-	-
200-250	2	218	274	56	61	978	5814	0
250-300	3	270	266	-4	31	367	14019	0
300-400	11	350	328	-22	51	384	14894	0
>400	5	418	308	-110	112	425	15543	0
total	22	333	313	-20	87	435	14261	0

[a] simplified notation; referring to means over the biomass ranges

Table 52. Validation results per biomass range for Tier 3 data at the original resolution for the 2020 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]				$[Mg/ha]^2$		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	2	218	309	91	118	996	6012	1
250-300	-	-	-	-	-	-	-	-
300-400	1	376	285	-91	91	438	24336	0
>400	2	428	286	-141	144	477	19392	1
total	5	334	295	-39	124	677	15029	1

[a] simplified notation; referring to means over the biomass ranges

Table 53. Validation results per biomass range for Tier 3 data at the original resolution for the 2021 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]						
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	1	206	249	43	43	1113	676	1
250-300	-	-	-	-	-	-	-	-
300-400	1	377	401	24	24	482	23716	0
>400	1	439	382	-57	57	530	23104	0
total	3	341	344	3	43	708	15832	0

[a] simplified notation; referring to means over the biomass ranges

Table 54. Validation results per biomass range for Tier 3 data at the original resolution for the 2021 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	*MD*	*RMSD*	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	[Mg/ha]						
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	1	206	249	43	43	1113	676	1
250-300	-	-	-	-	-	-	-	-
300-400	1	377	401	24	24	482	23716	0

>400	1	439	382	-57	57	530	23104	0
total	3	341	344	3	43	708	15832	0

[a] simplified notation; referring to means over the biomass ranges

Table 55. Validation results per biomass range for Tier 3 data at the original resolution for the 2022 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	1	206	240	34	34	1113	3025	0
250-300	-	-	-	-	-	-	-	-
300-400	1	378	381	3	3	534	24336	0
>400	1	440	250	-190	190	582	23409	1
total	3	341	290	-51	111	743	16923	0

[a] simplified notation; referring to means over the biomass ranges

Table 56. Validation results per biomass range for Tier 3 data at the original resolution for the 2023 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)^a$	$SE^2_{CCI}{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------						
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	1	206	247	41	41	1113	3844	0
250-300	-	-	-	-	-	-	-	-
300-400	-	-	-	-	-	-	-	-
>400	-	-	-	-	-	-	-	-
total	1	206	247	41	41	1113	3844	0

[a] simplified notation; referring to means over the biomass ranges

Table 57. Validation results per biomass range for Tier 3 data at the original resolution for the 2024 map.

AGB_{ref} bin	# plots	AGB_{ref}	AGB_{map}	MD	$RMSD$	$Var(Plt)^a$	$SE_{CCI}^2{}^a$	I_{Var}
[Mg/ha]	count	----------[Mg/ha] ----------				[Mg/ha]^2		
0-50	-	-	-	-	-	-	-	-
50-100	-	-	-	-	-	-	-	-
100-150	-	-	-	-	-	-	-	-
150-200	-	-	-	-	-	-	-	-
200-250	1	206	249	43	43	1113	3844	0
250-300	-	-	-	-	-	-	-	-
300-400	-	-	-	-	-	-	-	-
>400	-	-	-	-	-	-	-	-
total	1	206	249	43	43	1113	3844	0

[a] simplified notation; referring to means over the biomass ranges

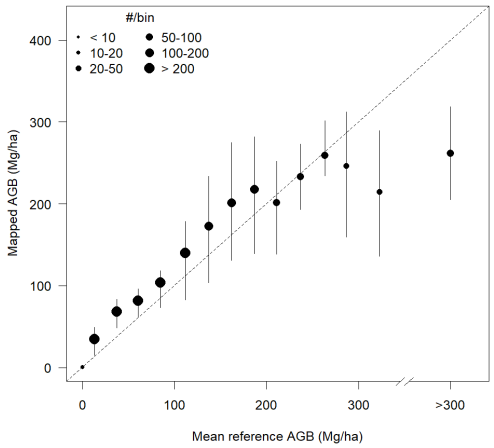
3.2.Tier 1 plot data spatially aggregated to 0.1° cells

The results of global AGM_{map} - AGB_{ref} comparisons using Tier 1 data (plot size ≤ 0.6 ha) spatially aggregated to 0.1° cells are shown in Figure 6 and Tables 58-75. The rightmost variance columns shown in the non-aggregated results are omitted here because spatial correlation of errors within 0.1° cells may be non-negligible, but we lack data to assess such correlation for most biomes at the current stage of the project.

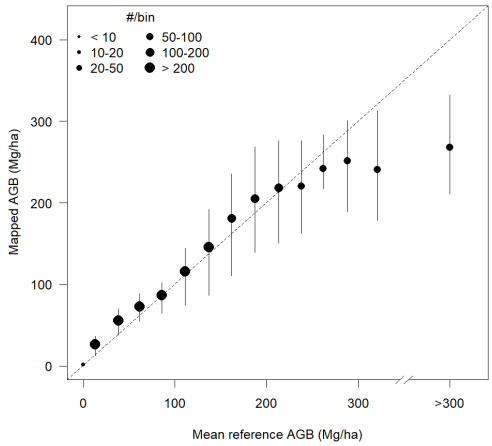
Spatial aggregation to 0.1° cells improved the fit between AGB_{ref} and AGB_{map} with absolute mean differences within 30 Mg/ha below 200 Mg/ha. Beyond 300 Mg ha^{-1}, AGB values are still under-predicted and the 0.1° cells producing the most under-prediction are located in southeast Australia. These cells show lower estimates than the previous version of CCI Biomass products (not shown here). The results of the 18 years for Version 7 of the CCI maps show less consistency than their previous versions, particularly 2005-2010 with more overestimation until 200 Mg/ha and the 2024 map with underestimation in the 200-300 Mg/ha bins. This could be an effect of using a different number of reference data (much more reference data used for the 2005-2019 maps, see Table 2).

Spatial aggregation reduced the effect of localized AGB fluctuations in the map and their potential interaction with plot-map geolocation mismatches. These results suggest the CCI Biomass predictions at 0.1° cell size are more precise than at the original pixel resolution. Note that at 0.1°, averages from both plots and maps correspond to the same forest definition (Section 2.4). Most 0.1° cells meeting the criterion of at least five plots per cell happen to be located in the temperate region (Section 3.5). Spatial aggregation also led to reduced inconsistency except for the 2024 results.

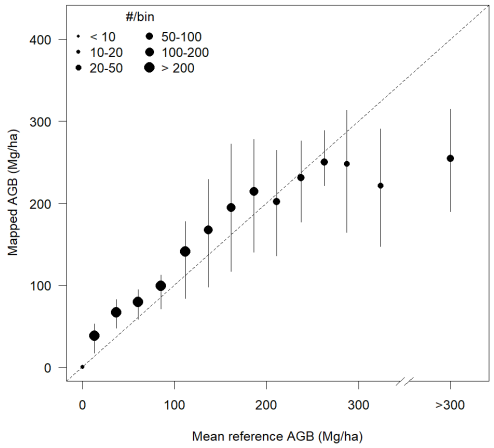
2005



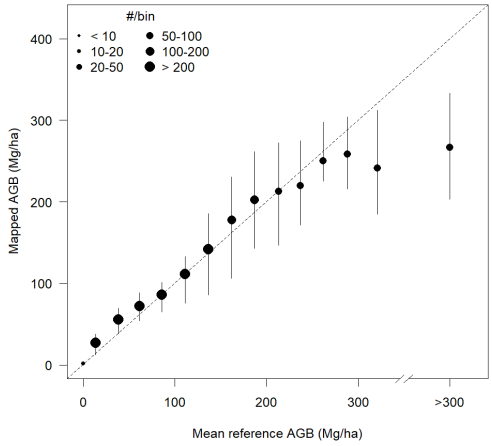
2016



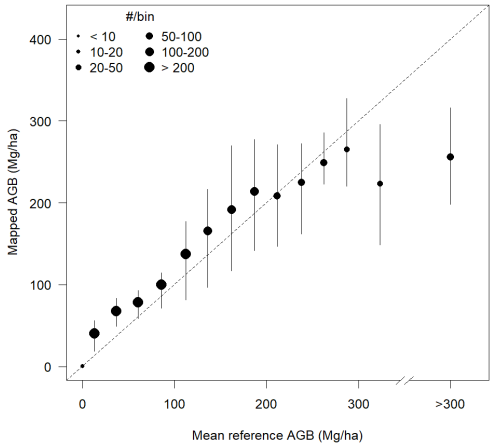
2006



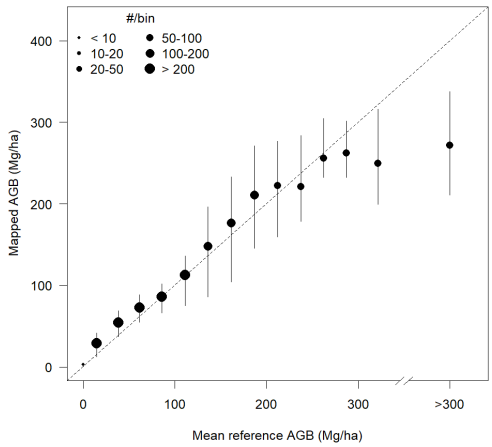
2017



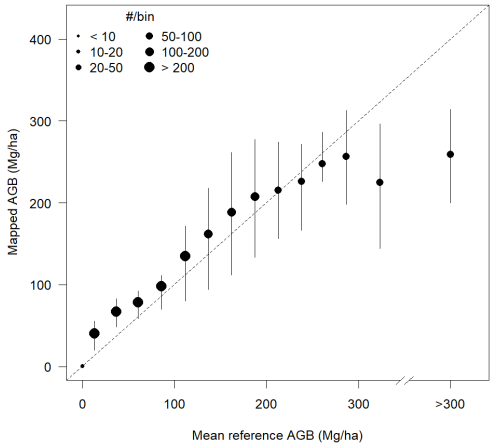
2007



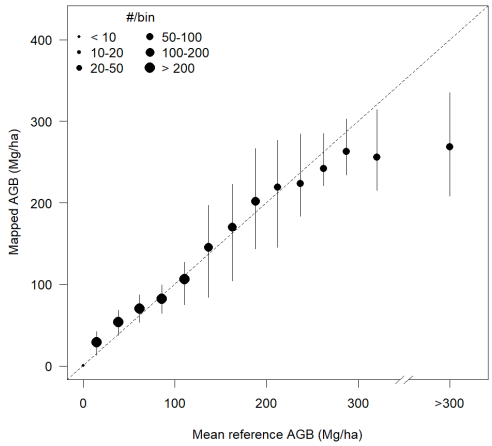
2018



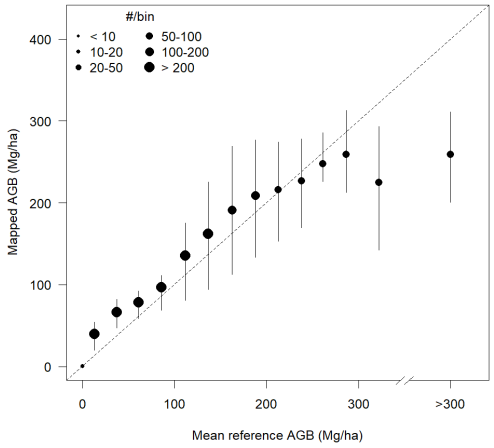
2008



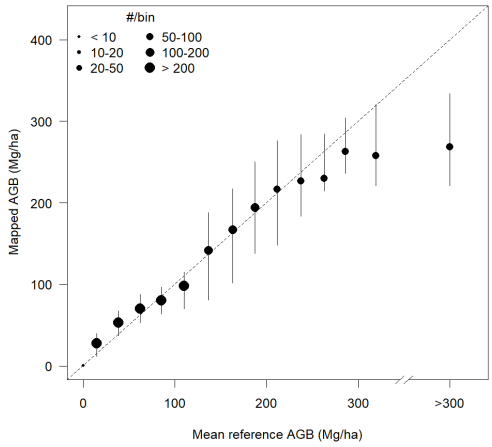
2019



2009



2020



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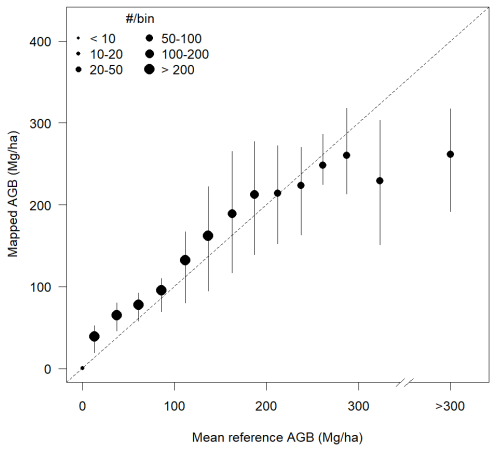
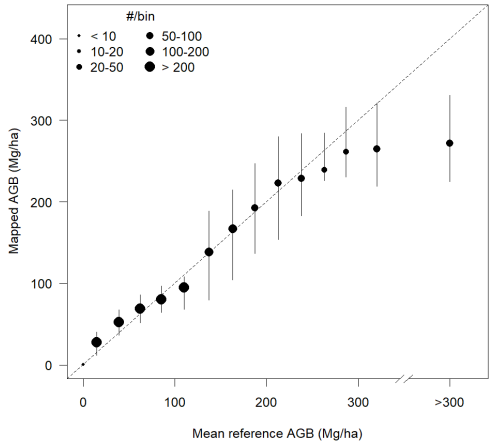


2021



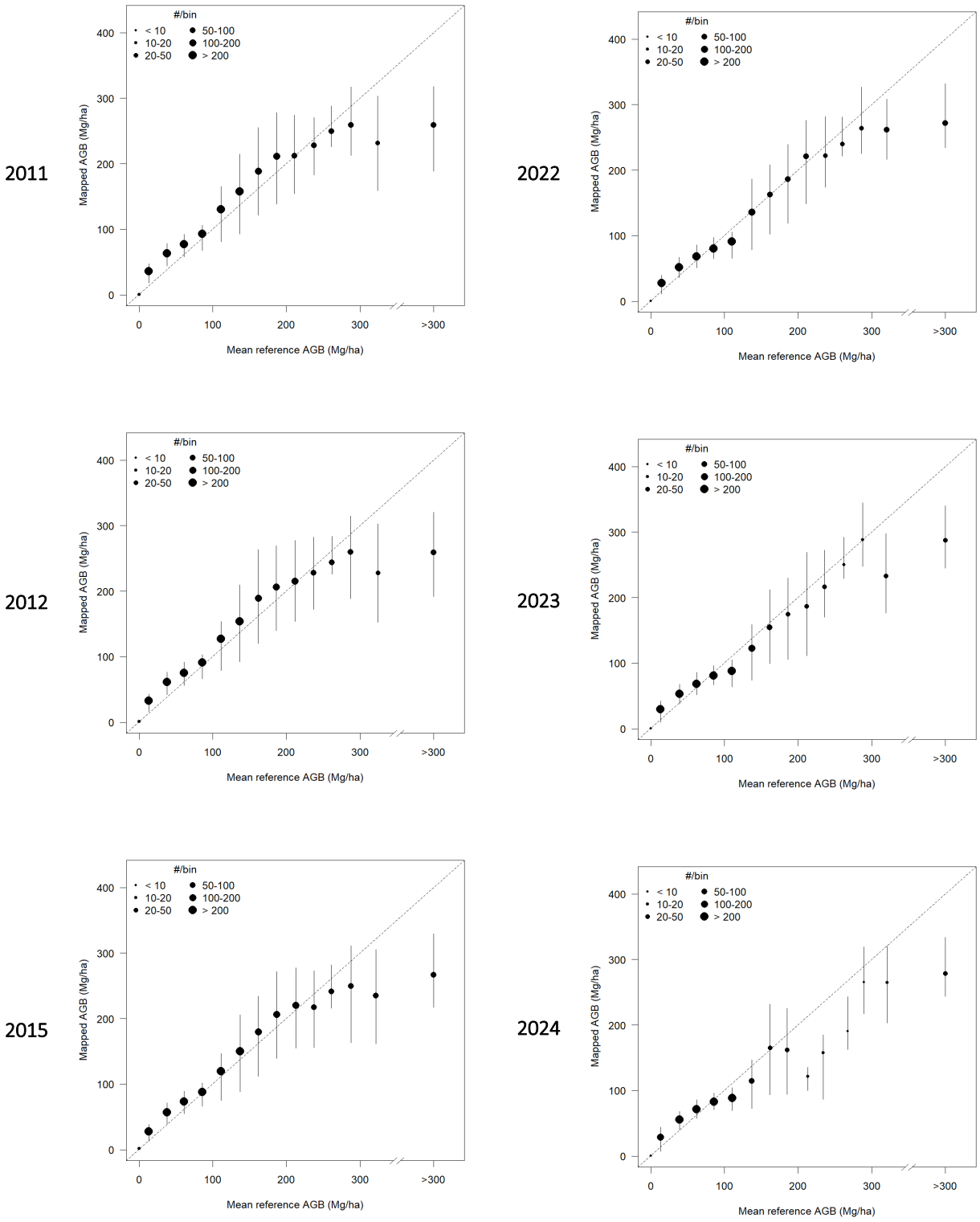


Figure 6. AGBref - AGBmap comparisons for Tier 1 data spatially aggregated to 0.1° and binned over 25 Mg/ha wide biomass ranges with whiskers representing the interquartile range of mapped AGB values and symbol size representing the number of 0.1° cells per AGB range. AGBref > 350 Mg/ha data are grouped into a single bin.

Table 58. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2005 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3208	26	53	27	38
50-100	1418	68	88	20	46
100-150	399	123	155	32	85
150-200	234	173	209	36	100
200-250	163	225	218	-7	84
250-300	101	273	254	-19	83
300-400	67	337	224	-113	144
>400	52	686	266	-420	495

Table 59. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2006 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3556	26	54	28	39
50-100	1494	68	86	18	43
100-150	415	123	153	30	85
150-200	250	173	204	31	97
200-250	167	225	217	-8	85
250-300	108	274	249	-24	87
300-400	70	340	223	-117	148
>400	52	691	267	-424	497

Table 60. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2007 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3757	26	55	29	40
50-100	1562	68	85	17	42
100-150	417	123	149	27	83
150-200	261	173	201	29	95
200-250	161	224	216	-8	88
250-300	115	273	256	-17	77
300-400	68	338	229	-109	139
>400	53	682	262	-420	493

Table 61. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2008 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3702	26	55	28	39
50-100	1615	68	84	16	41
100-150	442	122	146	24	82
150-200	268	174	197	24	94
200-250	159	224	220	-4	83
250-300	118	272	252	-21	83
300-400	70	338	226	-112	145
>400	52	692	271	-422	505

Table 62. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2009 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3643	26	54	28	38
50-100	1702	69	84	16	41
100-150	471	123	147	24	82
150-200	282	174	199	25	95
200-250	164	224	221	-3	85
250-300	122	273	253	-20	78
300-400	74	339	230	-109	141
>400	50	713	268	-445	537

Table 63. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2010 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3550	27	53	26	37
50-100	1779	69	83	14	40
100-150	485	123	145	22	81
150-200	278	173	200	26	94
200-250	167	224	218	-5	85
250-300	125	272	254	-19	78
300-400	74	340	233	-107	141
>400	50	711	272	-439	521

Table 64. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2011 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3440	27	51	24	35
50-100	1868	69	82	13	38
100-150	506	122	142	20	79
150-200	284	173	199	26	93
200-250	173	223	219	-4	82
250-300	125	272	254	-19	81
300-400	70	342	232	-110	143
>400	50	711	272	-438	509

Table 65. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2012 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3335	28	49	21	33
50-100	2002	69	80	11	37
100-150	547	121	138	17	77
150-200	295	172	197	24	91
200-250	178	223	221	-2	85
250-300	123	273	251	-22	79
300-400	68	342	231	-110	143
>400	52	699	269	-430	500

Table 66. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2015 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	3008	28	46	17	29
50-100	2231	69	78	9	34
100-150	604	121	131	10	72
150-200	312	173	192	19	90
200-250	178	223	219	-4	85
250-300	135	274	245	-28	88
300-400	81	339	237	-101	136
>400	52	694	279	-415	490

Table 67. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2016 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	2872	29	45	16	28
50-100	2333	70	77	8	34
100-150	629	121	127	6	71
150-200	316	174	192	18	89
200-250	183	224	220	-4	84
250-300	131	274	246	-28	84
300-400	83	336	244	-92	128
>400	54	683	275	-409	485

Table 68. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2017 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	2442	29	45	16	28
50-100	2327	70	77	7	33
100-150	628	121	123	2	66
150-200	306	173	189	16	88
200-250	175	224	216	-8	81
250-300	138	273	254	-19	80
300-400	87	335	242	-93	129
>400	55	678	276	-403	479

Table 69. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2018 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	1805	32	48	15	28
50-100	2184	70	77	7	34
100-150	503	120	125	5	67
150-200	254	174	193	19	89
200-250	150	224	222	-2	84
250-300	117	274	259	-15	75
300-400	92	335	252	-83	121
>400	55	679	277	-402	479

Table 70. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2019 map.

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	1566	32	47	15	26
50-100	2035	70	75	4	29
100-150	471	119	120	0	64
150-200	236	175	185	11	84
200-250	140	223	221	-2	88
250-300	115	274	251	-22	77
300-400	93	333	256	-77	116
>400	59	661	272	-389	466

Table 71. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2020 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	1414	33	46	14	25
50-100	1914	70	74	3	29
100-150	443	119	114	-6	63
150-200	221	174	180	6	81
200-250	148	224	221	-2	85
250-300	105	275	247	-28	79
300-400	96	333	257	-75	118
>400	60	659	273	-386	464

Table 72. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2021 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	1273	33	46	13	25
50-100	1764	71	73	2	28
100-150	418	120	111	-9	63
150-200	200	175	179	4	81
200-250	128	224	226	1	85
250-300	75	277	252	-24	78
300-400	84	336	267	-69	107
>400	57	694	272	-422	488

Table 73. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2022 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	----------[Mg/ha] ----------			
0-50	1122	33	46	13	25
50-100	1679	71	73	2	27
100-150	392	120	107	-13	62
150-200	172	173	174	0	80
200-250	113	222	222	0	88
250-300	66	275	254	-21	74
300-400	66	332	257	-75	111
>400	42	734	283	-452	583

Table 74. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2023 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	----------[Mg/ha] ----------			
0-50	900	33	48	15	25
50-100	1525	71	73	2	27
100-150	347	119	99	-20	58
150-200	108	172	163	-9	71
200-250	58	221	199	-22	83
250-300	29	275	270	-5	63
300-400	30	329	233	-95	132
>400	37	754	297	-457	594

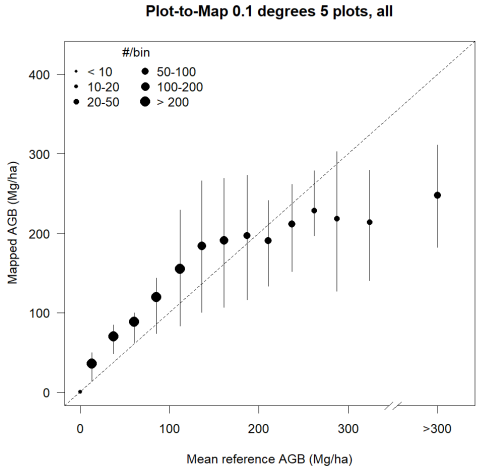
Table 75. Validation results per biomass range for Tier 1 data spatially aggregated to 0.1° cells for the 2024 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	----------[Mg/ha] ----------			
0-50	737	32	49	16	26
50-100	1268	72	76	4	24
100-150	307	118	96	-23	52
150-200	78	171	164	-7	77
200-250	21	223	139	-84	103
250-300	10	283	243	-40	84
300-400	20	336	252	-84	127
>400	21	765	296	-470	577

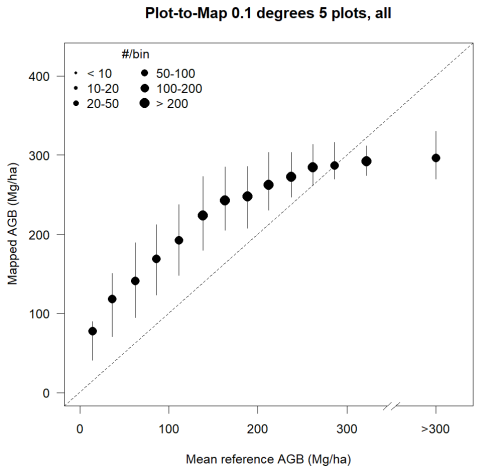
3.3.Comparisons with LiDAR-based, 1-km pixel Congo basin Forests AGB and EMAP 25-km aggregates

The results of the global AGM_{map} - AGB_{ref} comparisons at 0.1° resolution using LiDAR-based and CoFor AGB as reference data are shown in Figure 7 and Tables 76-85. The key observation is map overestimation in almost all the AGB bins until 300 Mg/ha for maps from 2007 and onwards. This is mainly driven by the new dataset (EBA-ALS) in Amazonia (Csilik *et al*. 2024). The overestimation subsides for maps from 2022-2024. On the other hand, the 2007-2010 results may be influenced by the CoFor data having a dense plot network in the forest management areas of the Congo Basin. Since the original plot data inside the 1-km aggregates of the CoFor dataset are unavailable, we were unable to account for partly deforested areas. Such areas are likely to exist given the active forestry activities in the area. On the other hand, similar results were observed using the plot data (Tier 2 plots in particular), which builds confidence in using LiDAR and CoFor data for accuracy assessments.

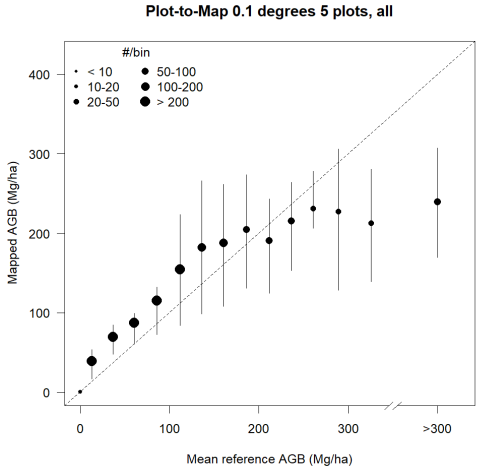
2005



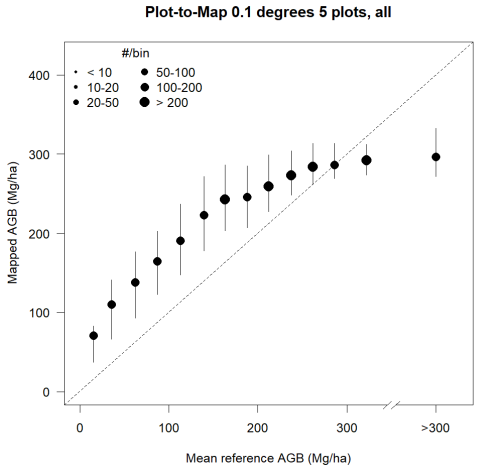
2016



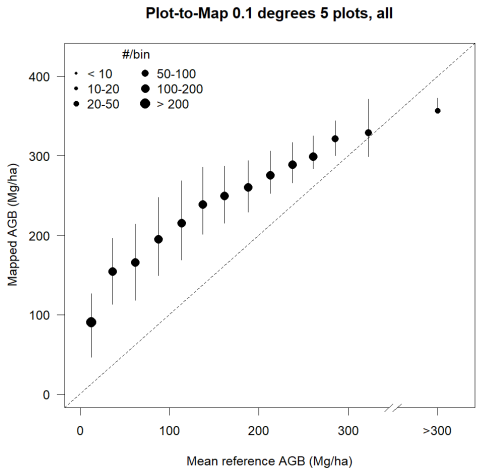
2006



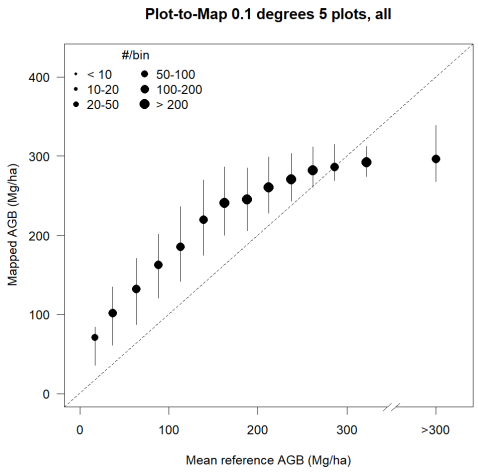
2017



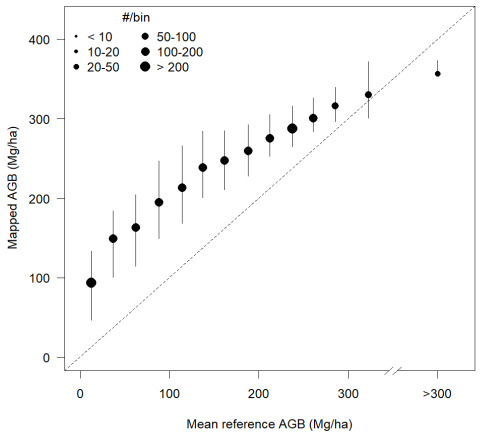
2007



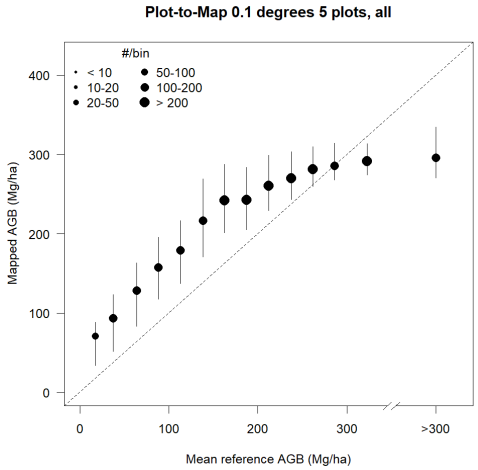
2018



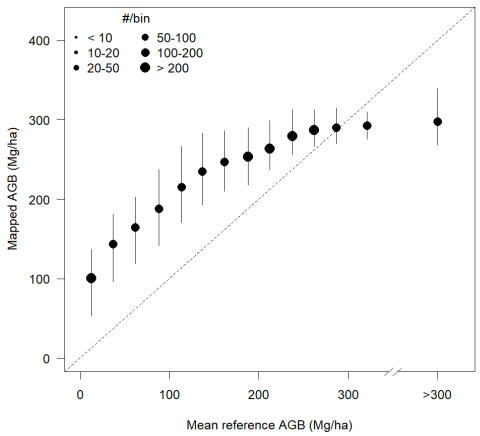
2008



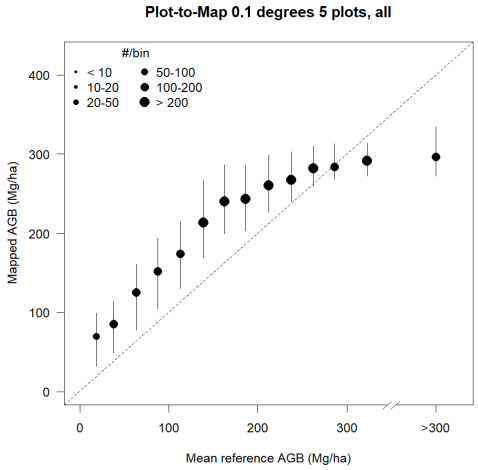
2019



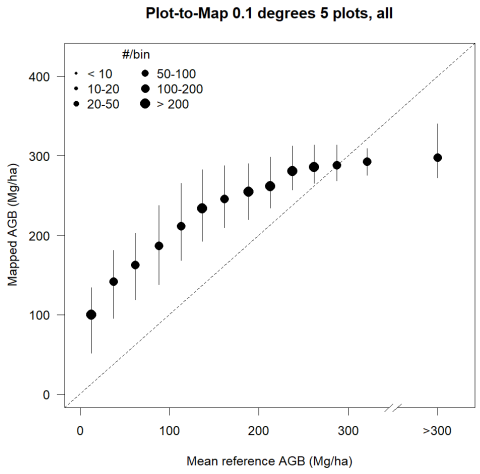
2009



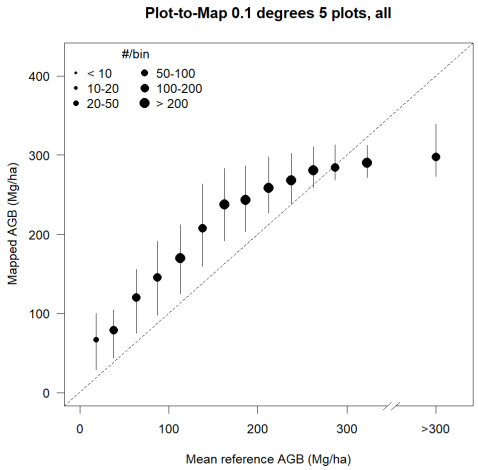
2020



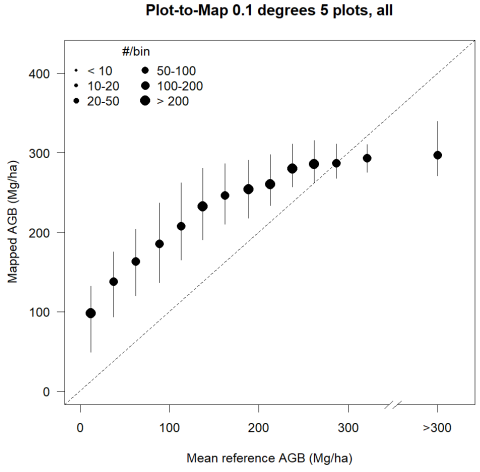
2010



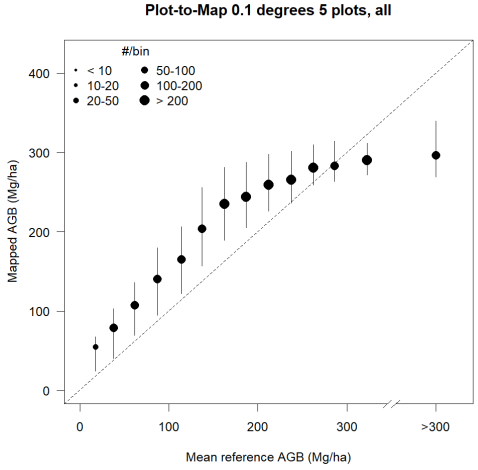
2021



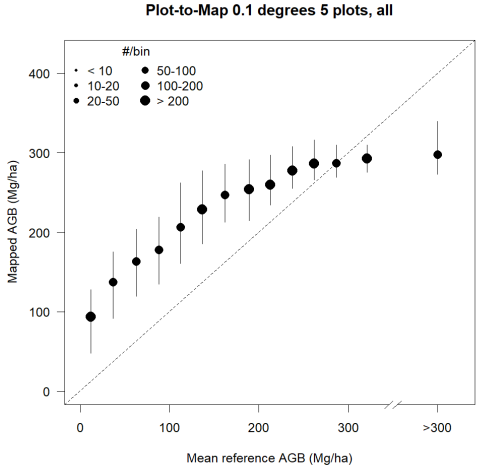
2011



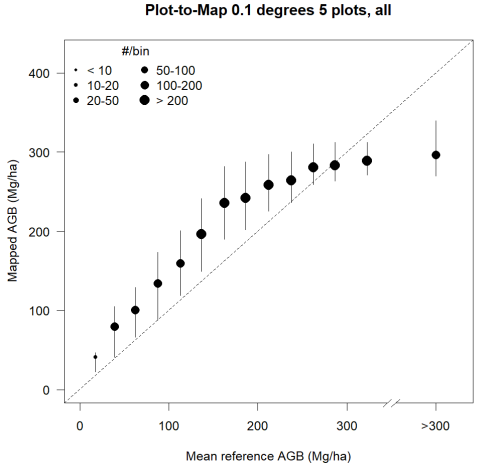
2022



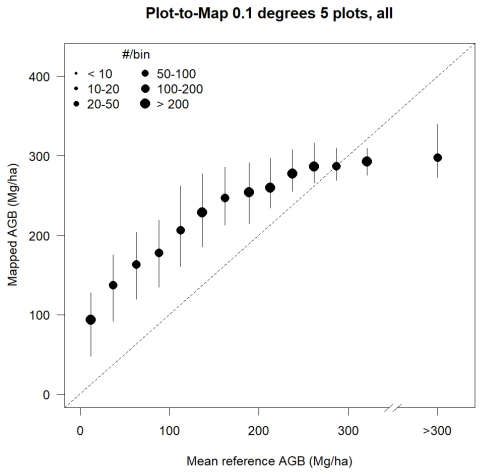
2012



2023



2015



2024

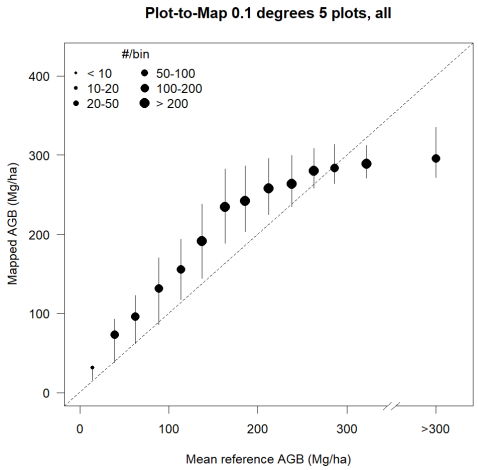


Figure 7. AGBref - AGBmap comparisons for LiDAR-based and CoFor AGB data spatially aggregated to 0.1° and binned over 25 Mg/ha wide AGB ranges with whiskers representing the interquartile range of mapped AGB values and symbol size representing the number of 0.1° cells per AGB range. AGBref > 350 Mg/ha data are grouped into a single bin.

Table 76. Validation results per biomass range using c-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2007 map.

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	79	19	59	40	104
50-100	45	74	104	31	74
100-150	35	121	139	18	60
150-200	20	173	212	39	74
200-250	51	229	311	82	123
250-300	100	277	348	71	109
300-400	210	345	379	34	72
>400	30	429	389	-39	78
total	570	241	281	41	89

Table 77. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2010 map.

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	79	19	60	40	103
50-100	45	74	101	27	73
100-150	35	121	135	15	56
150-200	20	173	207	35	70
200-250	51	229	309	80	121
250-300	100	277	347	70	108
300-400	210	345	378	33	72
>400	30	429	389	-39	78
total	570	241	280	39	88

Table 78. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2015 map.

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	254	15	22	7	35
50-100	91	72	109	37	88
100-150	46	126	141	15	61
150-200	25	177	194	17	68
200-250	41	230	264	35	109
250-300	76	274	322	48	113
300-400	75	335	350	15	68
>400	9	437	356	-81	109
total	617	130	149	19	72

Table 79. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2016 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	79	19	59	40	104
50-100	45	74	96	22	65
100-150	35	121	133	12	54
150-200	20	173	204	31	68
200-250	51	229	303	74	119
250-300	100	277	344	68	107
300-400	210	345	376	31	72
>400	30	429	389	-40	77
total	570	241	278	37	88

Table 80. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2017 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	247	14	23	8	31
50-100	89	73	108	35	97
100-150	46	124	120	-4	59
150-200	26	172	172	0	70
200-250	26	227	183	-44	82
250-300	39	276	270	-6	108
300-400	51	340	328	-12	69
>400	9	440	362	-78	108
total	533	109	114	4	66

Table 81. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the

2018 map

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	250	15	23	8	31
50-100	74	76	111	35	105
100-150	57	122	115	-7	56
150-200	26	173	170	-3	66
200-250	26	226	173	-53	77
250-300	38	276	267	-9	109
300-400	34	332	318	-14	83
>400	3	460	395	-65	143
total	508	98	102	3	67

Table 82. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2019 map

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	246	15	23	8	31
50-100	79	76	106	30	103
100-150	53	123	121	-2	56
150-200	26	171	159	-12	68
200-250	15	225	159	-66	82
250-300	29	276	257	-19	126
300-400	23	337	335	-2	89
>400	3	461	400	-61	147
total	474	87	91	5	68

Table 83. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2020 map

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	246	14	23	8	26
50-100	74	76	108	32	111
100-150	54	123	118	-4	53
150-200	28	171	153	-18	65
200-250	13	224	163	-61	73
250-300	12	278	232	-46	146
300-400	15	342	338	-3	92
>400	2	461	396	-65	177
total	444	74	79	5	65

Table 84. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2021 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	79	19	61	41	111
50-100	45	74	97	23	69
100-150	35	121	130	9	53
150-200	20	173	197	25	67
200-250	51	229	299	70	118
250-300	100	277	343	66	107
300-400	210	345	376	31	73
>400	30	429	389	-40	76
total	570	241	277	36	89

Table 85. Validation results per biomass range using LiDAR-based and CoFor AGB data spatially aggregated to 0.1° cells for the 2022 map

AGB_{ref} bin	# cells	AGB_{ref}	AGB_{map}	*MD*	*RMSD*
[Mg/ha]	count	[Mg/ha]			
0-50	237	15	20	6	18
50-100	75	77	112	35	121
100-150	57	124	139	16	52
150-200	23	171	159	-12	64
200-250	13	222	163	-59	72
250-300	11	278	251	-27	128
300-400	15	344	337	-7	93
>400	-	-	-	-	-
total	431	73	81	8	65

The 0.25° results using the 2017 EMAP dataset as reference data are shown in Figure 8 and Table 86. The rest of the epochs were excluded as the results were very similar. All maps show underestimation starting from $AGB_{ref} \approx 300$ Mg/ha as indicated by six 0.1° grid cells. Note that fewer reference data are available as AGB increases.

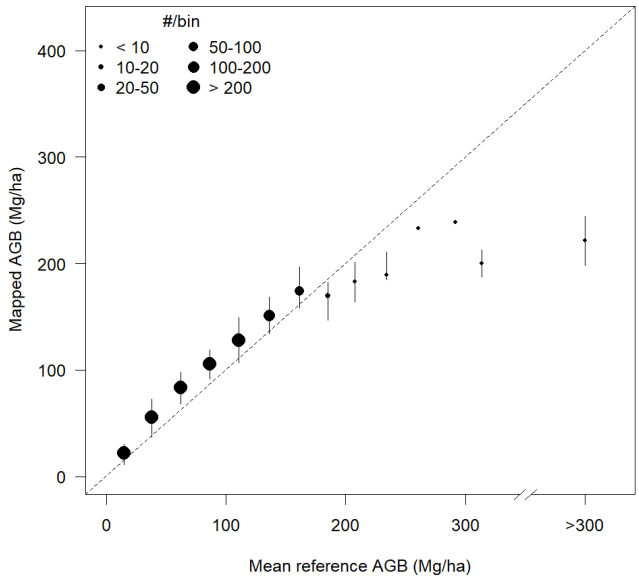


Figure 8. AGBref - AGBmap comparisons for EMAP AGB data spatially aggregated to 0.25° and binned over 25 Mg/ha wide AGB ranges with whiskers representing the interquartile range of mapped AGB values and symbol size representing the number of 0.25° cells per AGB range. AGBref > 350 Mg/ha data are grouped into a single bin.

Table 86. Validation results per biomass range using EMAP AGB data spatially aggregated to 0.25° cells for the 2017 map.

AGB_{ref} bin [Mg/ha]	# cells count	AGB_{ref} [Mg/ha]	AGB_{map} [Mg/ha]	*MD* [Mg/ha]	*RMSD* [Mg/ha]
0-50	1617	28	41	13	24
50-100	1691	73	93	20	30
100-150	481	119	135	17	33
150-200	67	167	173	6	37
200-250	12	225	187	-38	57
250-300	2	276	236	-40	42
300-400	4	339	211	-128	132
total	3874	62	79	16	29

To facilitate interpretation, the bias and RMSD estimates per map for different AGB_{ref} bins differentiated by Tier are shown in Table 87 and Table 88, respectively.

Figure 9. Legend for colour schemes used in summary tables of bias and RMSD.

Figure 9 provides the legend for the colour schemes used in these tables.

Table 87 shows that for the mid-range of AGB_{ref}, bias is within 20% of AGB_{ref} for Tier 1 data (which is consistent with GCOS requirements (GCOS, 2015)) but not for Tier 2 or 3 data. For the range between 250 and 400 Mg/ha the bias is usually less than 30% of $AGB_{ref.}$ At the lower and upper ends of the AGB range considered, bias always exceeds 20%. The RMSD exceeds 20% in all cases except for Tier 3 in 2015-2021 when AGB_{ref} exceeds 250-300 Mg/ha (Table 88). This means map error is dominated by the random component rather than the bias.

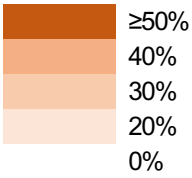


Figure 9. Legend for colour schemes used in summary tables of bias and RMSD.

Table 87. AGB bias [Mg/ha] differentiated per Tier and per AGB bin. Colour shading is based on relative bias; legend in Figure 9.

Tier 1 non-aggregated

AGB_{ref} (Mg/ha)	2005	2006	2007	2008	2009	2010	2011	2012	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0-50	45	44	45	46	46	46	45	43	44	43	43	46	40	41	41	41	44	42
50-100	26	23	22	21	19	18	15	12	8	6	11	24	19	18	15	13	10	10
100-150	7	3	3	3	1	1	-1	-4	-8	-11	-10	-5	-11	-12	-15	-17	-22	-26
150-200	-23	-26	-28	-28	-29	-28	-28	-29	-25	-22	-28	-28	-39	-44	-51	-56	-60	-62
200-250	-39	-42	-43	-43	-45	-51	-51	-51	-54	-56	-60	-59	-66	-72	-80	-89	-93	-89
250-300	-70	-71	-71	-72	-74	-79	-78	-80	-84	-87	-90	-85	-87	-101	-114	-123	-131	-116
300-400	-117	-118	-118	-120	-121	-135	-133	-134	-133	-137	-137	-123	-116	-134	-143	-158	-170	-139
>400	-513	-506	-503	-502	-505	-496	-493	-493	-488	-493	-494	-531	-561	-611	-617	-677	-726	-678
Total	1	1	1	0	-2	-6	-8	-11	-16	-19	-21	-17	-24	-28	-30	-30	-31	-21

Tier 2 non-aggregated

AGB_{ref} (Mg/ha)	2005	2006	2007	2008	2009	2010	2011	2012	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0-50	58	56	55	56	42	48	41	20	7	-4	-5	-9	-25	-36	-36	-38	-37	
50-100	108	100	108	81	86	89	82	60	60	41	53	1	4	-1	0	-8	-52	36
100-150	86	79	79	84	72	76	74	81	70	69	77	20	17	24	17	27	44	-5
150-200	52	56	54	77	57	65	61	51	45	46	32	4	10	-1	24	8	18	13
200-250	29	31	32	32	12	20	19	14	-7	4	9	-14	-6	0	-6	-12	-1	56
250-300	45	50	54	47	27	43	43	43	13	-2	7	1	-8	-7	-17	-56	-24	9
300-400	-80	-79	-72	-57	-48	-67	-62	-61	-74	-70	-79	-77	-93	-85	-86	-80	-75	-59
>400	-288	-266	-268	-274	-282	-275	-276	-281	-283	-263	-269	-267	-326	-330	-334	-349	-352	-381
Total	-18	-17	-16	-15	-25	-22	-24	-28	-42	-41	-45	-79	-92	-106	-109	-123	-106	-101

Tier 3 non-aggregated

AGB_{ref} (Mg/ha)	2005	2006	2007	2008	2009	2010	2011	2012	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0-50																		
50-100																		
100-150	253	251	249	127	97	271	269	266	323	156	-8	271	253					
150-200																		
200-250	70	68	80	40	32	86	105	101	32	50	89	91	56	91	43	34	41	43
250-300	-31	-15	-16	-7	15	-9	-10	-11	-11	9	20	4	-4					
300-400	-29	-30	-31	-61	-9	-49	-50	-51	-61	-74	-50	-34	-22	-91	24	3		
>400	-67	-68	-69	-59	-103	-108	-109	-110	-93	-63	-67	-91	-110	-141	-57	-190		
Total	-7	-9	-9	-26	-8	-21	-20	-22	-32	-36	-29	-16	-20	-39	3	-51	41	43

Table 88. Root mean square difference (RMSD) is differentiated per Tier and per AGB bin. Column headings are exactly the same as table above (Table 87).

Tier 1 non-aggregated

AGB_{ref} (Mg/ha)	20 05	20 06	20 07	20 08	20 09	20 10	20 11	20 12	20 15	20 16	20 17	20 18	20 19	20 20	20 21	20 22	20 23	20 24
0-50	79	76	77	76	76	77	76	75	75	73	73	76	62	63	62	62	62	60
50-100	78	73	70	68	66	65	64	64	64	64	67	73	59	60	57	56	54	55
100-150	91	87	86	85	85	86	86	86	80	80	78	79	70	70	69	71	68	69
150-200	106	104	103	103	104	104	104	105	100	100	98	100	96	96	96	95	95	95
200-250	121	121	120	121	120	124	124	124	122	123	123	125	125	125	127	126	125	127
250-300	139	137	137	137	137	142	142	143	140	141	145	146	146	152	158	164	167	161
300-400	174	173	173	174	175	187	187	188	181	184	185	175	167	182	190	202	207	190
>400	866	856	854	851	853	830	827	826	819	822	826	893	942	995	1011	1094	1145	1121
Total	174	168	165	165	165	167	167	167	165	167	176	191	200	208	207	200	198	173

Tier 2 non-aggregated

AGB_{ref} (Mg/ha)	20 05	20 06	20 07	20 08	20 09	20 10	20 11	20 12	20 15	20 16	20 17	20 18	20 19	20 20	20 21	20 22	20 23	20 24
0-50	125	118	116	117	94	104	96	85	79	47	44	48	27	36	36	39	37	
50-100	179	172	180	147	153	149	142	118	136	114	128	73	77	75	90	103	81	97
100-150	153	143	142	147	136	138	133	134	126	118	123	68	62	85	69	87	85	82
150-200	120	134	132	151	152	150	150	146	123	118	109	87	92	83	106	95	95	89
200-250	123	132	124	119	108	117	115	114	94	91	104	91	99	101	114	118	121	99
250-300	115	117	119	124	116	118	117	118	91	90	95	94	84	86	81	88	74	59
300-400	149	150	146	132	130	126	126	124	113	115	127	119	119	121	113	118	110	104
>400	401	381	382	389	383	379	383	390	378	368	376	373	428	426	444	448	447	467
Total	206	199	198	198	193	194	195	196	188	183	194	200	219	232	243	252	240	241

Tier 3 non-aggregated

AGB_{ref} (Mg/ha)	20 05	20 06	20 07	20 08	20 09	20 10	20 11	20 12	20 15	20 16	20 17	20 18	20 19	20 20	20 21	20 22	20 23	20 24
0-50																		
50-100																		
100-150	253	251	249	127	97	271	269	266	323	156	8	271	253					
150-200																		
200-250	94	103	107	56	51	148	146	148	46	66	124	111	61	118	43	34	41	43
250-300	59	56	56	45	82	47	47	47	42	33	55	33	31					
300-400	99	99	100	103	98	90	91	91	72	96	95	60	51	91	24	3		
>400	81	79	79	100	108	125	126	127	94	66	90	99	112	144	57	190		
Total	98	98	98	86	91	111	111	112	93	83	89	90	87	124	43	111	41	43

3.4.Assessments by ecoregion

To allow assessments of validation results over different ecoregions, spatially aggregated comparisons of AGB_{ref} and AGB_{map} were stratified by biomes (Dinerstein *et al*., 2017). The 2010 and 2021 results are presented in Figures 10 and 11 while the 2015-2024 results are omitted due to their similarity to the 2021 results. Several strata had limited data or no data at all (e.g., deserts, flooded grassland, etc.). These cases are not included here.

The main biomes, namely temperate broadleaf and mixed forests, and tropical and subtropical moist broadleaf forest, exhibit good agreement with reference data; and the results improve from 2010 to 2021. For the boreal forests, mangroves, temperate grassland savannas and shrublands and tundra biomes, reasonable fits with minor over-predictions are found in the lower AGB ranges. A few plots in the boreal and tundra (arctic zones) exhibit high biomass while the map depicts low biomass. Map over- and under-prediction are mostly present in tropical and subtropical dry broadleaf forest and and temperate broadleaf and mixed forest. Note that data in the dry tropical regions are limited, which hampers drawing solid conclusions. Spikes of map under-prediction are also found in tropical and subtropical grasslands, which is the opposite of the previous version where over-prediction was observed in these biomes. Under-prediction was also observed in Mediterranean forests, woodland and scrub around the 120 Mg/ha bin. The AGB_{ref} density at which under-prediction starts differs by biome. For boreal forests, saturation of AGB_{map} occurs at approximately 110 Mg/ha, for example. The strong similarity of results for the temperate broadleaf and mixed forests biome (Figures 10-11) with those of the spatially aggregated results obtained with the Tier 1 data (Figure 6) was already mentioned above. Such similarity is also present between results from tropical and subtropical moist broadleaf forest and results from Tier 2 and LiDAR/CoFor.

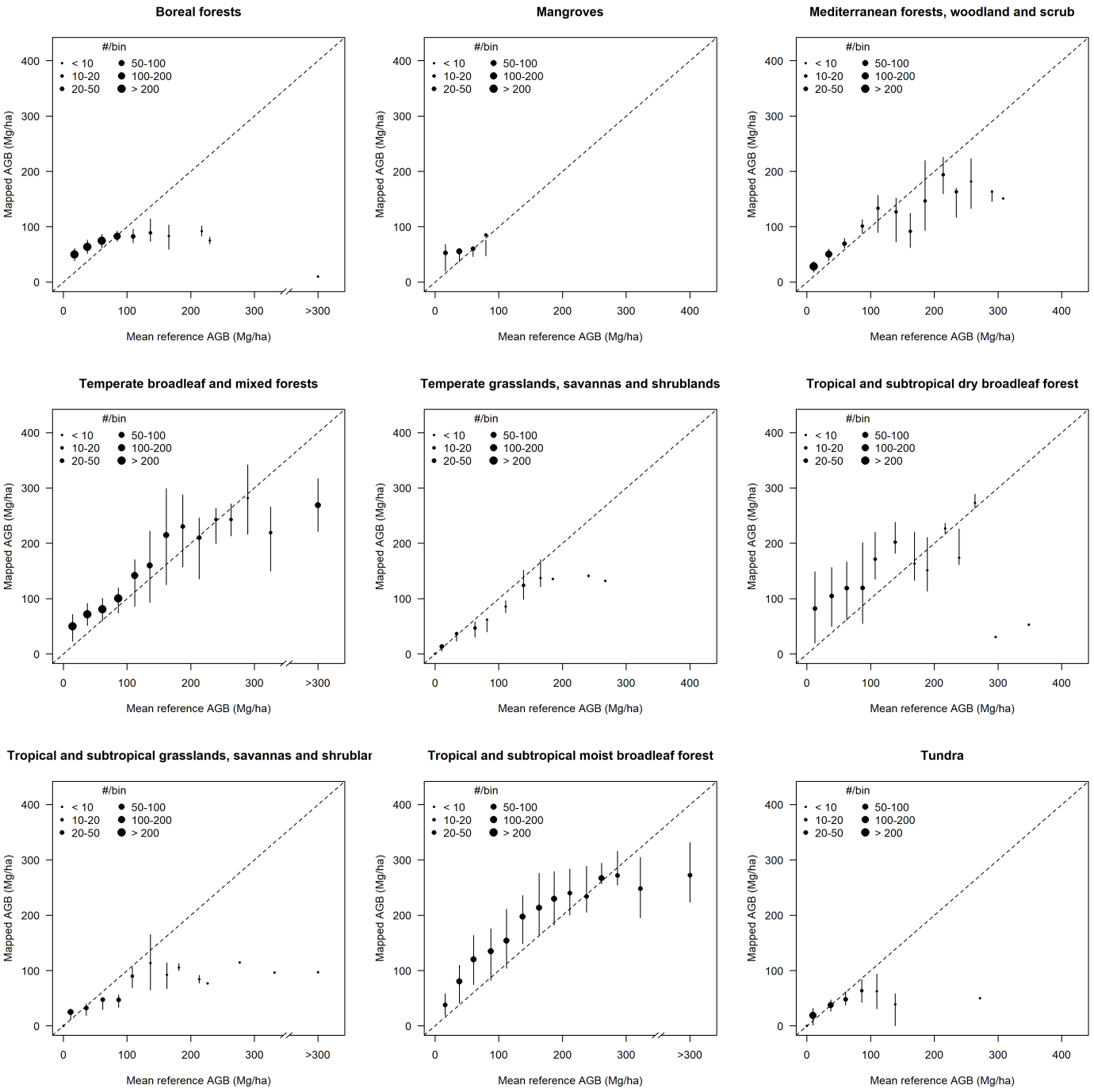


Figure 10. Comparisons between AGB_{ref} and the **2010** AGB map per biome (Dinerstein *et al.*, 2017) using all available data binned over 25 Mg/ha wide biomass ranges with whiskers representing the interquartile range of mapped biomass values and symbol size representing the number of 0.1° cells per biomass range.

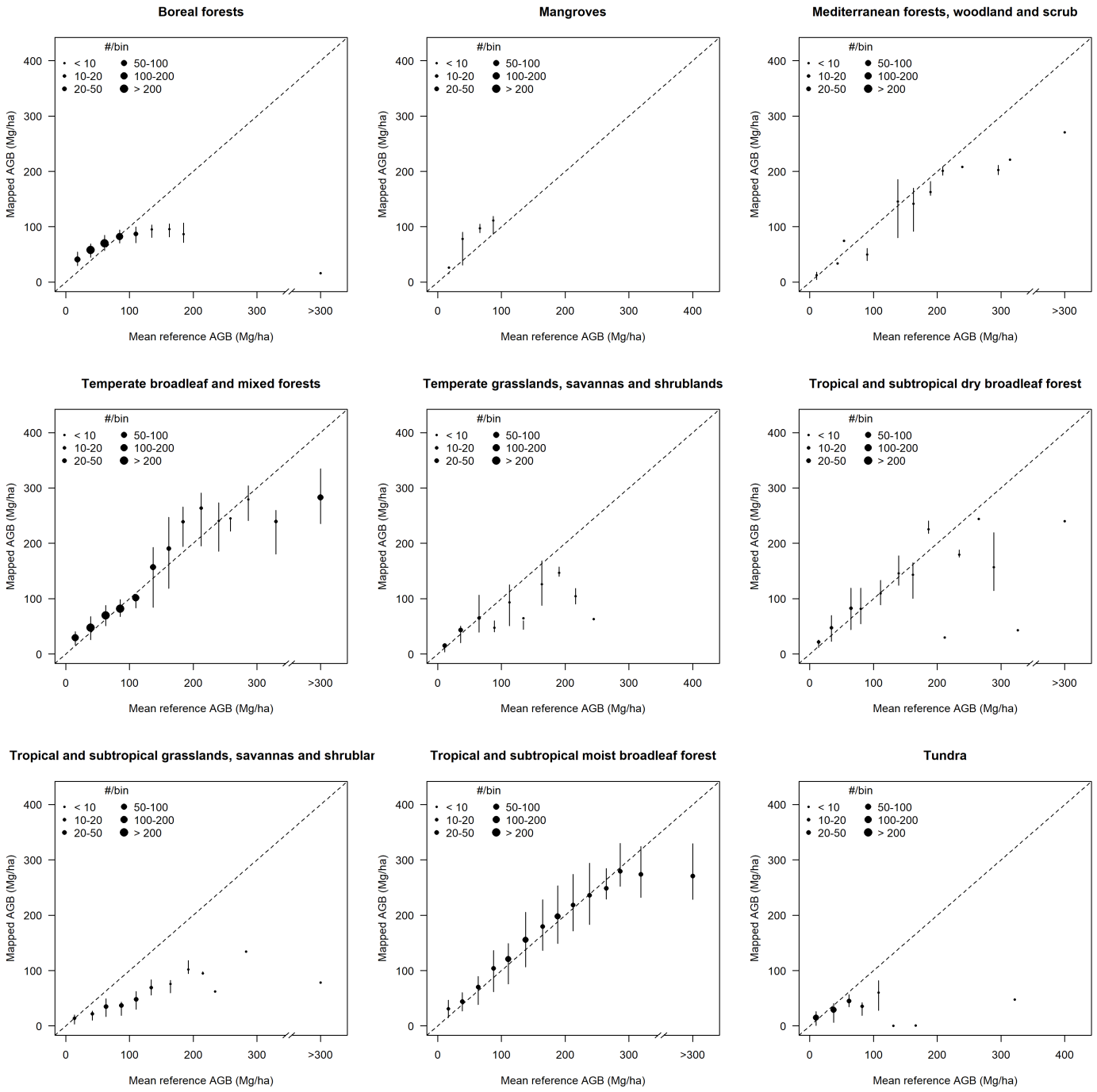


Figure 11. Comparisons between AGB_{ref} and the **2021** AGB map per biome (Dinerstein *et al.*, 2017) using all available data binned over 25 Mg/ha wide AGB ranges with whiskers representing the interquartile range of mapped AGB values and symbol size representing the number of 0.1° cells per AGB range.

3.5. User-led validation

Schelkovo Forest Enterprise, near Moscow, Russia

The Schelkovo Forest Enterprise lies northeast of Moscow (37.7°-38.5° E, 55.8°-56.2° N). A stand-wise forest management inventory was completed in 2020. Forest inventory professionals compared the previous inventory's forest map (2004) to recent very high-resolution imagery, updating polygons where canopy changes were detected. During the field campaign, every polygon (whether changed or stable) was visited to record updated forest descriptions, including species composition and growing stock volume, with a target error of ≤ 15%.

Aboveground biomass (AGB) for each forest stand (polygon) was calculated from growing stock volume, species, site index and stand age. These stand level polygons were then rasterised to 10 m pixels and aggregated to a 100 m grid, retaining only pixels entirely covered by ground-truth data. This process yielded approximately 28,000 CCI Biomass pixels.

Notably, a series of bark beetle outbreaks in the area caused significant tree mortality followed by partial recovery, complicating mapping efforts. There is some temporal mismatch between forest loss recorded with CCI AGB and very high-resolution imagery.

The comparison shows a clear biomass-dependent bias in CCI Biomass. Both v6 and v7 strongly overestimate AGB in low-biomass areas, with bias decreasing as biomass increases, then shifting to underestimation at around 150–180 t/ha. Underestimation is strongest in high-biomass stands (>200 t/ha), consistent with saturation effects. Overall, v7 shows lower bias and random error across most biomass ranges, especially at 75–150 t/ha, while v6 performs slightly better in the highest biomass class.

Table 89. Validation results using the Schelkovo reference dataset: comparison of CCI Biomass v5 and v6.

Inventory AGB		CCI-AGB_v6			CCI-AGB_v7			# pixels
range	Average	AGB	RMSD	ME	AGB	RMSD	ME	
1-25	16	86	89	70	89	89	73	1'604
26-50	38	112	94	74	113	90	75	2'487
51-75	64	139	96	75	135	87	71	3'312
76-100	89	155	88	66	148	77	59	4'409
101-125	113	160	72	47	152	62	39	5'303
126-150	138	162	60	24	154	50	16	5'449
151-175	162	174	54	12	160	45	-1	3'995
176-200	184	187	49	3	167	44	-17	1'281
201-262	216	188	53	-28	174	62	-42	193
Total	**107**	**152**	**107**	**90**	**145**	**96**	**76**	**28'033**

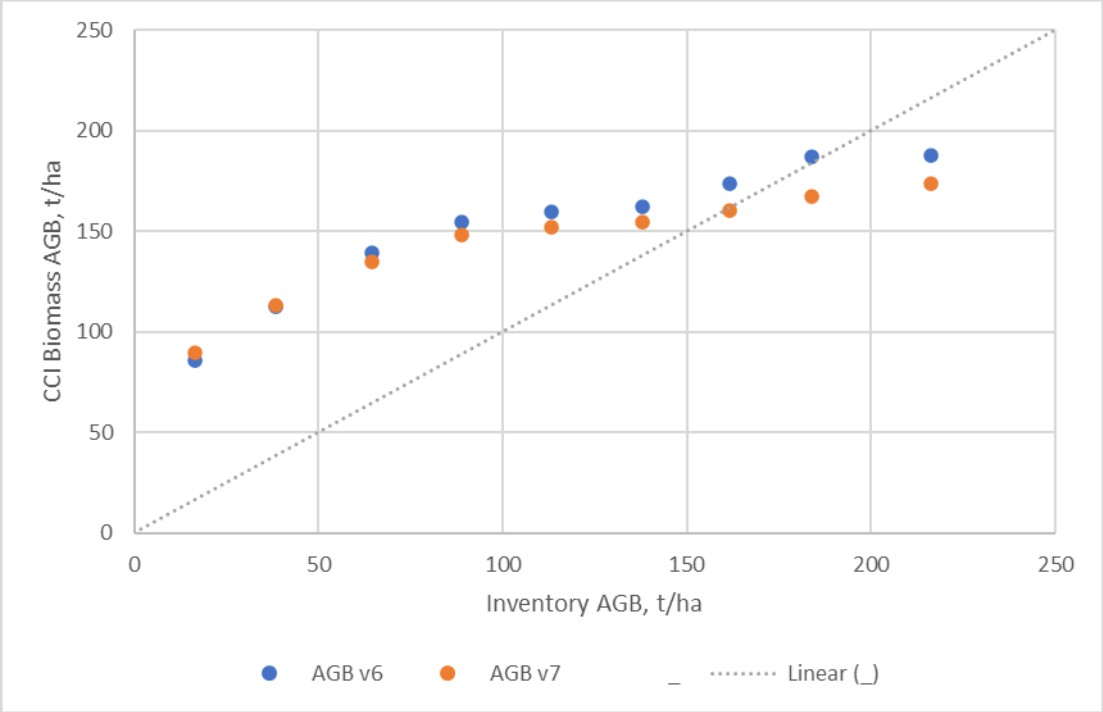


Figure 12. Binned scatterplots of the comparisons between Schelkovo reference dataset and the two CCI Biomass versions.

Both AGB estimations overestimate biomass across most of the range, except at the highest values. This overestimation is slightly greater in v6, although v6 more accurately captures high-biomass stands.

GEO-TREES plots in Russia

The GEO-TREES network (https://data.geo-trees.org/) provides open access to large (> 0.25 ha) research plots with accurate geolocation. In Russia, 184 plots are available. Validation results (Table 90 and Figure 14) show that CCI biomass underestimate AGB above 200 t/ha, although this bias is merely the same among the two map versions.

Table 90. Agreement between GEO-TREES research plots and CCI Biomass AGB data

Inventory AGB		CCI-AGB_v6			CCI-AGB_v7			# pixels
Range	Average	AGB	RMSD	ME	AGB	RMSD	ME	
1-50	25	28	21	3	53	44	28	16
51-100	77	86	62	9	97	58	20	20
101-150	132	170	70	38	167	60	35	38
151-200	175	206	52	31	194	41	20	44
201-250	221	200	60	-21	189	61	-32	41
251-300	268	221	64	-47	207	74	-61	20
301-380	341	233	112	-108	224	121	-118	5
Total	167	171	86	4	167	84	-1	184

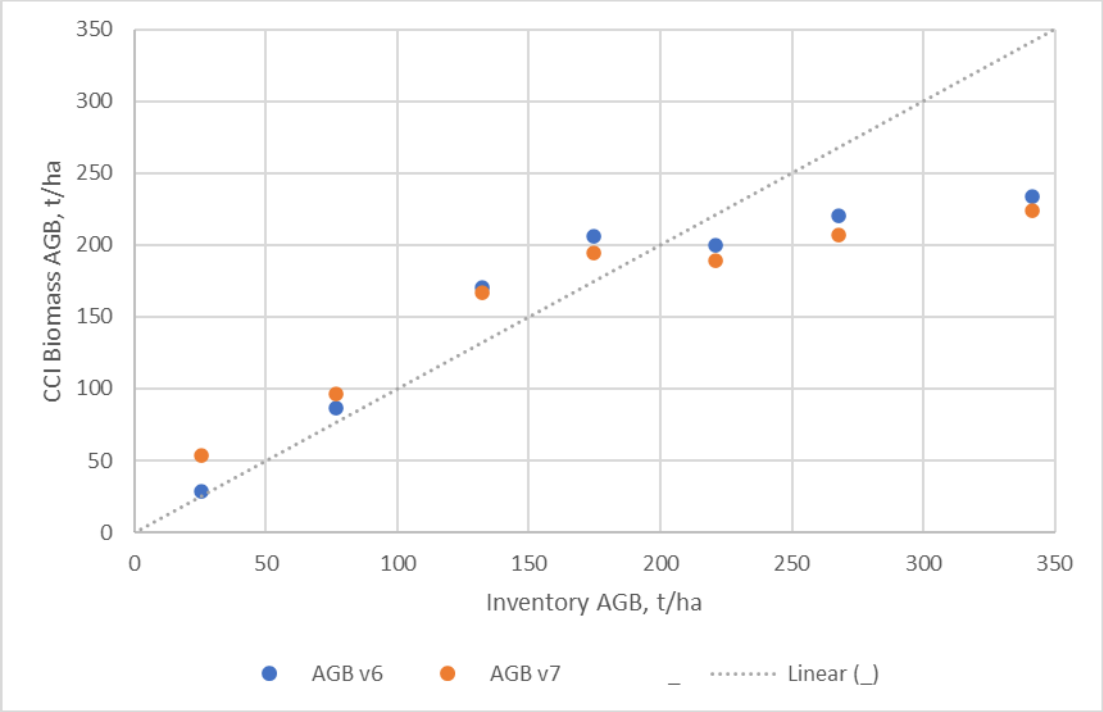


Figure 13. Binned scatterplots comparing the GEO-Trees reference dataset with CCI Biomass *Versions* 6 and 7.

CCI Biomass *Versions* 6 and 7 are compared almost similar with reference data except for the 25 t/ha bin. However, both versions still underestimates in high biomass forests.

Comparison with the Brazil National Forest Inventory

Data and methods

The Brazilian National Forest Inventory (Inventário Florestal Nacional – IFN) is an ongoing, nationwide survey coordinated by the Serviço Florestal Brasileiro. It is based on a systematic sampling design using a 20 × 20 km grid that spans all Brazilian biomes, comprising more than 10,000 sampling points. As of December 2024, the IFN has surveyed approximately 513 million hectares of both natural and planted forests across Brazil. This effort includes measurements of over 900,000 individual trees, the identification of around 8,400 species—including 13 newly described ones—and socio-environmental interviews with more than 38,000 community members. Biome-level coverage currently includes 100% of the Pampa, 78% of the Cerrado, 71% of the Caatinga, 58% of the Atlantic Forest (Mata Atlântica), and 44% of the Amazon, with the Pantanal scheduled for complete coverage next (Serviço Florestal Brasileiro, n.d.)

Each standard plot consists of four subplots, positioned 50 meters from the plot center in cardinal directions. Within each subplot, ten sampling parcels are established, each measuring 10 × 10 meters (0.01 hectares). This results in a sampling area of 0.1 hectares per subplot, and consequently 0.4 hectares per plot under the standard design (Figure 15). In the Amazon biome, the sampling intensity is increased to account for the presence of larger trees. An additional ten parcels per subplot are established specifically to sample trees with a diameter at breast height (DBH) greater than 40 cm. This expansion doubles the sampling area to 0.2 hectares per subplot, resulting in a total of 0.8 hectares per plot. The total plot area (including both sampled and unsampled ground) is 200 × 200 meters (4 hectares) under the standard configuration, and 300 × 300 meters (9 hectares) in the Amazon biome, where larger plots accommodate the increased sampling effort (Serviço Florestal Brasileiro, 2021).

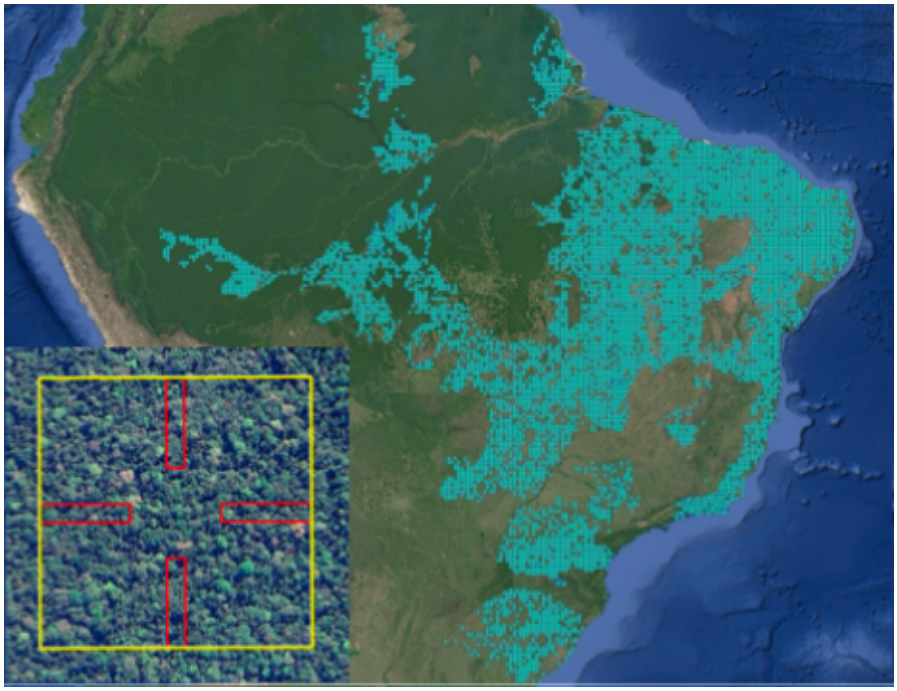


Figure 14. Plot design and spatial distribution of currently available NFI plots. The yellow area represents the total plot extent (4 ha), while the red rectangles indicate subplots covering 20 × 50 m each.

In this exercise, we used tree-level data available through the web-portal of the Serviço Florestal Brasileiro. Using tree measurements (DBH and tree height) we estimated the aboveground biomass of individual trees based on Chave *et al*. (2014) pan-tropical allometric equation:

$$agb = 0.0673 * (wd * DBH^2 * height)^{0.976}$$

For wood density (wd), we applied a mean value of 0.632 g/cm^3, representative for South American Tropical forests of Chave *et al*. (2009). Total biomass was then calculated by summing the estimated tree-level AGB within each subplot or plot and normalizing to a per-hectare basis.

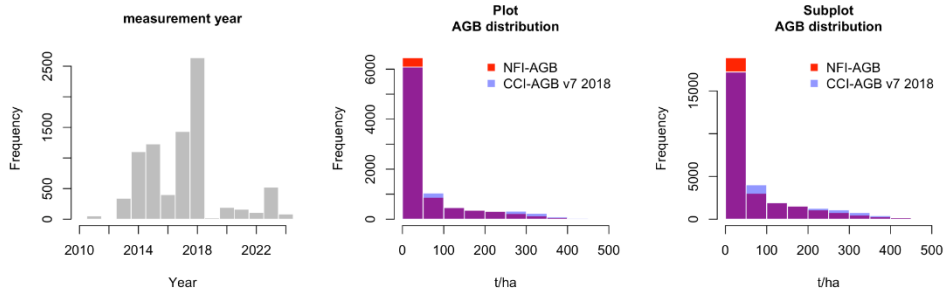


Figure 15. Acquisition year of NFI plots (a); AGB distribution from the NFI at the plot (b) and at the subplot levels (c) with corresponding estimates from the CCI Biomass v7 2018 product.

Since the majority of NFI plots were sampled in 2018 (Figure 16a), we used the CCI Biomass v7 product from the same year for comparison.

The pixel size of CCI Biomass product (100x100 m) does not match the dimensions of a plot or subplot, so we extracted the mean value of the CCI biomass map over each corresponding (sub)plot area.

Agreement between the NFI data and the ESA CCI product improves from the subplot- to plot-level estimates. Aggregating subplot data to the plot-level reduces the variability associated with smaller sampling units and helps to mitigate the impact of outliers (Figure

17). Because many NFIs plots possess low AGB values (<10 t/ha), we truncated the data to NFI AGB > 10 t/ha (Figure 17, middle column) and to NFI AGB > 50 t/ha (Figure 17, right column). The relatively high correlation observed when using the full dataset is likely driven by the large number of plots with low biomass (<50 t/ha). When these low biomass plots are excluded, the correlation between NFI and ESA CCI estimates decreases, and shows a general overestimation of the ESA CCI product at higher biomass levels (> 100 t/ha) (Figure 17).

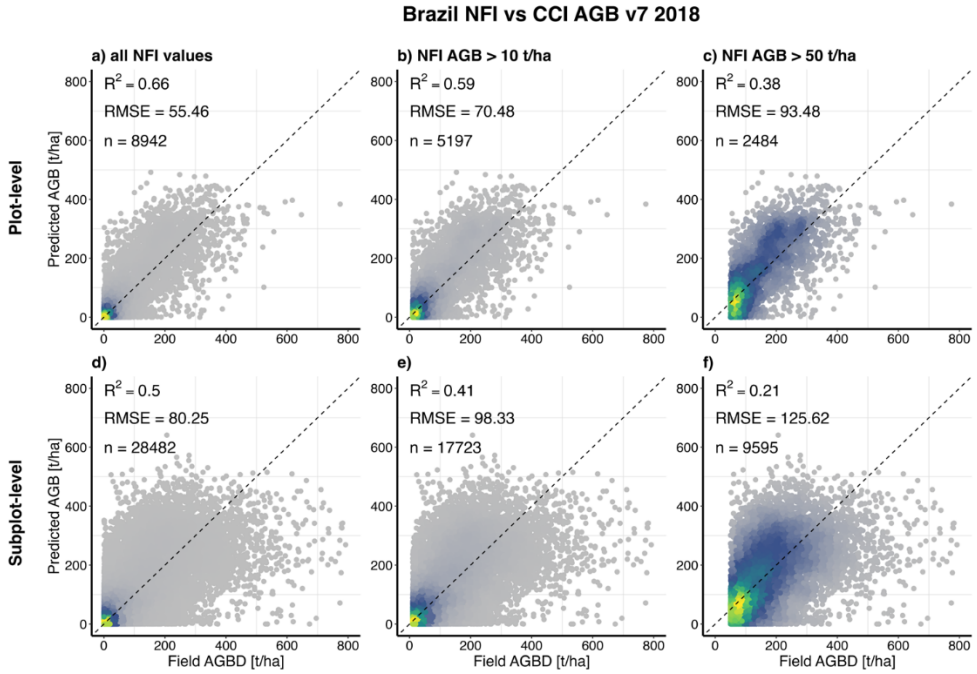


Figure 16. Comparison between Brazilian NFI and the ESA CCI Biomass v7 2018 product at the plot level (top row) and subplot level (bottom row). To address the high frequency of low AGB values in the NFI data (<10 t/ha), comparisons are also shown for subsets where NFI AGB exceeds 10 t/ha (middle column) and 50 t/ha (right column). Colors indicate density of the plots i.e, yellow the densest.

Finally, we evaluated ESA CCI Biomass product on an aggregated, binned scale. For this, we first divided the NFI values into 100 equal-sized percentile bins. For each bin, we then calculated the median NFI value, the median CCI estimate, and the standard deviation of the CCI values (displayed as error bars) (Figure 18). As in the full-data scatterplot (Figure 17), the ESA CCI product slightly overestimates AGB in the low-to-mid range (<200 t/ha). In contrast, it underestimates biomass at very high values (>250 t/ha), although those estimates are based on relatively few samples.

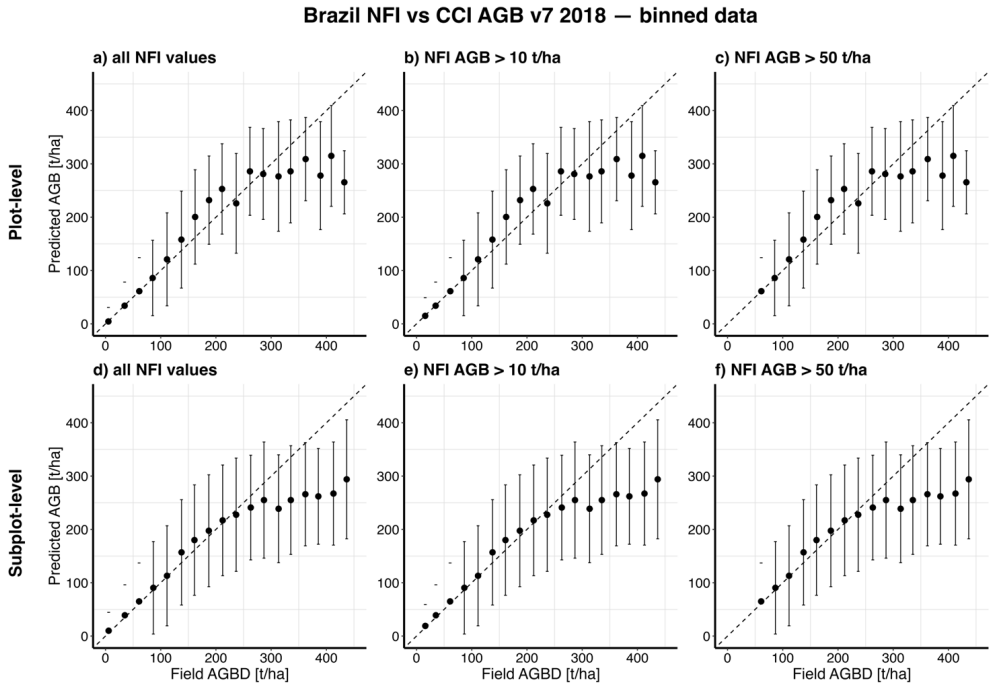


Figure 17. Binned comparison of AGB between the Brazilian NFI and the ESA CCI Biomass v7 2018 product at the plot level (top row) and subplot level (bottom row). NFI values were divided into 100 equal-sized percentile bins; for each bin, median NFI and CCI AGB are plotted, with CCI standard deviations shown as error bars. Panels show (left) all data, (middle) NFI AGB > 10 t/ha, and (right) NFI AGB > 50 t/ha.

Bearing in mind, that the Brazilian NFI represents a fully independent reference dataset, the overall correlation of the ESA CCI biomass product shows a strong agreement in the low-to-mid biomass range (0-200 t/ha), showing only a very slight positive bias. As expected, in the very high biomass range (250-300 t/ha), it is challenging to resolve the full biomass distribution. Currently, only a limited number of field plots exist in undisturbed Amazonian forests; as more plots are collected and made available over time, sampling density will increase and our understanding of the limitations of global remote-sensing biomass maps will improve.

3.6.Summary tables of the assessments by ecoregion

To facilitate interpretation of the AGB maps, we here summarise the bias and RMSD estimates for different AGB_{ref} bins by biome. Given the similarity in the results, only the 2010 and the 2021 comparisons are shown, see Tables 92-95.

The tables re-emphasize our overall finding that in the lower and higher AGB ranges the bias and RMSD are larger than in the mid-ranges. The bias for the mid-ranges for most biomes is around or below 20%, while the RMSD is above 20%.

The quantity of available reference information differs for different regions and there is lower confidence for some with limited reference data, including the (sub-)tropical dry forests and grasslands, mangroves, temperate grasslands and tundra.

Table 91. AGB bias [Mg/ha] per biome and per AGB bin for the 2010 map. Colour shading is as in Figure 9.

AGB_{ref} [Mg/ha]	Boreal	Mangrove	Mediterranean	Temperate broadleaf/mixed	Temperate grasslands, savannas and shrublands	Tropical/subtropical dry broadleaf	tropical and subtropical grasslands	Tropical and subtropical broadleaf forest	Tundra
0-50	28	22	17	36	3	71	7	64	6
50-100	10	1	11	20	-17	47	-23	100	-16
100-150	-32		4	26	-18	56	-20	100	-61
150-200	-82		-54	45	-32	-29	-72	34	
200-250	-140		-40	-5	-100	-15	-134	-2	
250-300	0		-94	-21	-135	9	-162	-21	-221
300-400	-389		-157	-126			-251	-90	
>400	-495			-444				-357	
Total	19	15	11	18	-8	51	-9	70	-2

Table 92. Root mean square difference (RMSD) per biome and per AGB bin for the 2010 map. Colour shading is based on the legend shown in Figure 9; column headings are as above.

AGB_{ref} [Mg/ha]	Boreal	Mangrove	Mediterranean	Temperate broadleaf/mixed	Temperate grasslands, savannas and shrublands	Tropical/subtropical dry broadleaf	tropical and subtropical grasslands	Tropical and subtropical broadleaf forest	Tundra
0-50	33	44	21	48	17	100	23	91	20
50-100	21	37	20	43	34	95	38	128	29
100-150	44		71	86	48	96	49	131	81
150-200	89		74	109	60	88	79	91	
200-250	141		73	92	100	37	135	92	
250-300	0		111	72	135	23	162	77	221
300-400	389		157	151			252	120	
>400	495			530				362	
Total	34	42	32	93	35	95	51	116	31

Table 93. AGB bias [Mg/ha] per biome and per AGB bin for the 2021 map. Colour shading is as in Figure 9. (shading not automatic)

AGB_{ref} [Mg/ha]	Boreal	Mangrove	Mediterranean	Temperate broadleaf/mixed	Temperate grasslands, savannas and shrublands	Tropical/subtropical dry broadleaf	tropical and subtropical grasslands	Tropical and subtropical moist broadleaf forest	Tundra
0-50	19	40	0	16	6	20	-12	30	0
50-100	6	78	-20	5	-12	32	-40	80	-26
100-150	-26		7	1	-37	1	-63	81	-69
150-200	-82		-24	34	-41	18	-89	66	-165
200-250			-22	22	-135	-43	-133	-11	
250-300			-93	-30		-50	-149	-11	
300-400	-356		-101	-96		-160	-286	-77	-274
>400	-623			-436				-324	
Total	9	44	-26	-7	-12	12	-46	57	-10

Table 94. Root mean square difference (RMSD) per biome and per AGB bin for the 2021 map. Colour shading is as in Figure 9; column headings are as above.

AGB_{ref} [Mg/ha]	Boreal	Mangrove	Mediterranean	Temperate broadleaf/mixed	Temperate grasslands, savannas and shrublands	Tropical/subtropical dry broadleaf	tropical and subtropical grasslands	Tropical and subtropical moist broadleaf forest	Tundra
0-50	26	58	9	37	28	37	20	51	22
50-100	20	94	38	30	42	48	50	108	36
100-150	38		98	65	60	66	69	120	86
150-200	87		65	94	60	69	95	113	165
200-250			26	112	141	49	136	96	
250-300			95	65		55	149	61	
300-400	356		102	128		160	286	97	274
>400	623			502				334	
Total	31	62	61	100	48	51	66	108	38

3.7.AGB map intercomparison

In this section, we assess the stability of map error among the current (Version 7) 18 CCI-Biomass AGB products, compare the most recent 2010, 2017-2020 versions with the Version 3 products, and compare the CCI maps with other AGB map products.

Stability of AGB_{map} – AGB_{ref} differences among the 2007-2012 and 2015-2024 AGB products

According to the World Meteorological Organization (2011), the user requirement for stability is, in general a requirement on the extent to which the error of a product remains constant over a longer period. To assess the stability of plot-map differences over the map years, Figure 19 illustrates the stability of AGB_map – AGB_ref differences assessed using a correlation matrix of residuals across all available map years (2005–2024). Overall, high temporal consistency was indicated, with most year-pairs showing strong agreement (R^2 typically > 0.85), particularly within contiguous periods such as 2010–2012 and 2015–2020. The highest consistency

was observed among the 2015–2020 products, where the R^2 frequently exceeded 0.90, confirming stable error structures over this interval. In contrast, earlier years (2005–2008) and the most recent epochs (2023–2024) show comparatively lower agreement with other periods (R^2 ~0.6–0.8), indicating shifts in residual patterns

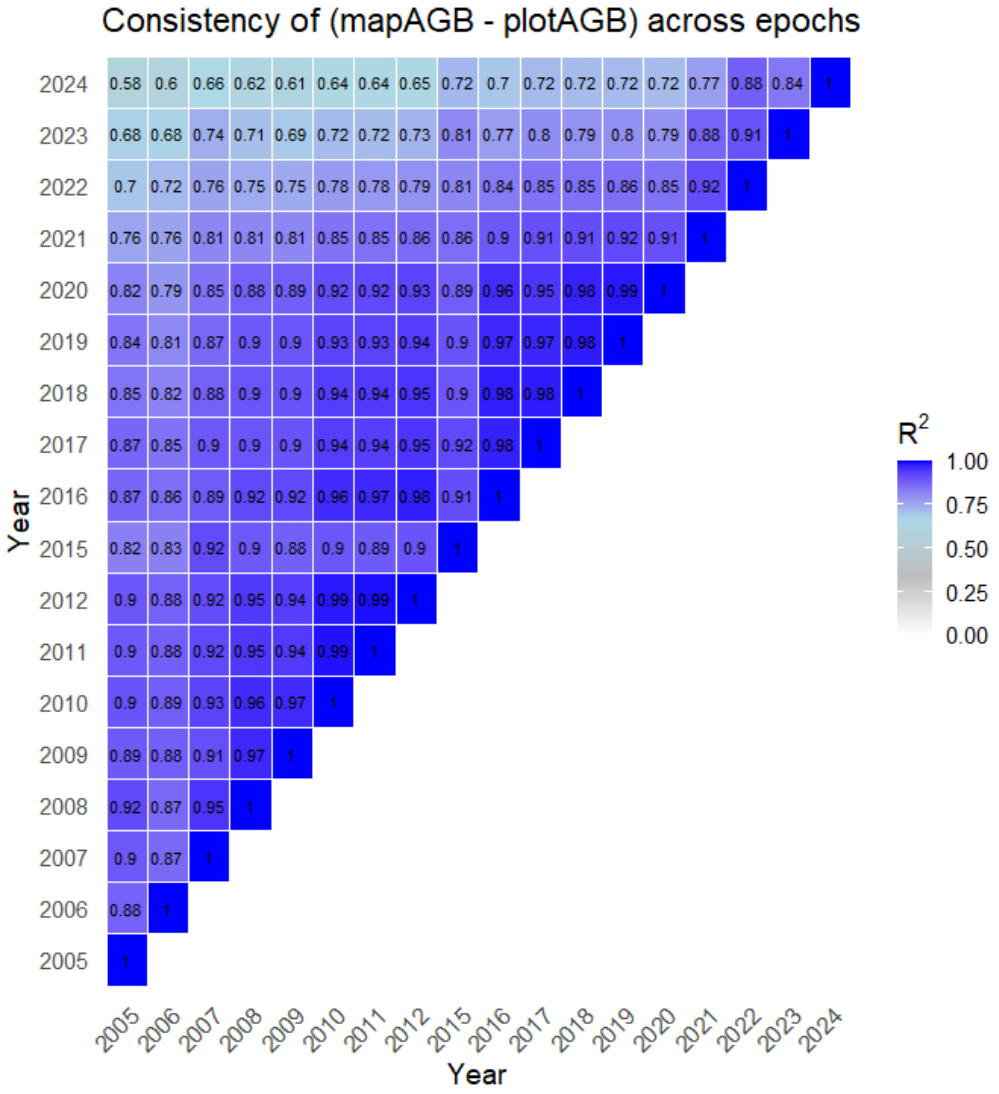


Figure 18. AGB residuals between harmonized Tier 1-3 plot data and mapped AGB at 0.1° cell level for each pair of map reference years. The red dashed line is the 1:1 line.

The map producer may want to know where the largest instabilities in the residuals occur. Such information is provided in Figures 20-22 where the locations of the 5% most negative differences between the 2010 and 2017 products (2010 – 2017; i.e., points above the 1:1 diagonal in Figure 19) are plotted as red circles whilst the 5% largest positive differences (i.e., points below the 1:1 diagonal) are shown by blue crosses. Several sites have entirely either large positive or large negative differences but in other places, such as east Australia, Madagascar, the northern Balkans and Mexico (Yucatán), both extremes occur close to one another. Figure 21 is a virtually identical figure showing the locations of cells with the most extreme differences between 2010 and 2018 residuals while Figure 22 does so for the 2017 and 2018 residuals. This analysis is part of the previous PVIR.

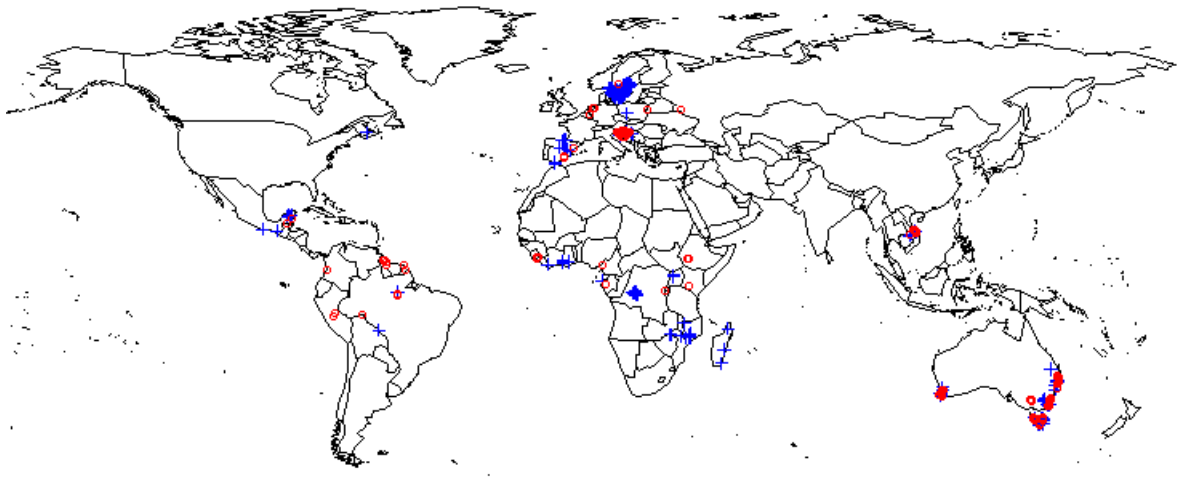


Figure 19. Locations of 0.1° cells with the most extreme differences between residuals in the 2010 and 2017 AGB products (2010 – 2017). The 5% cells with the most negative differences (i.e., 2017 > 2010) are indicated in red whilst the 5% largest positive differences (i.e., 2017 < 2010) are shown in blue.

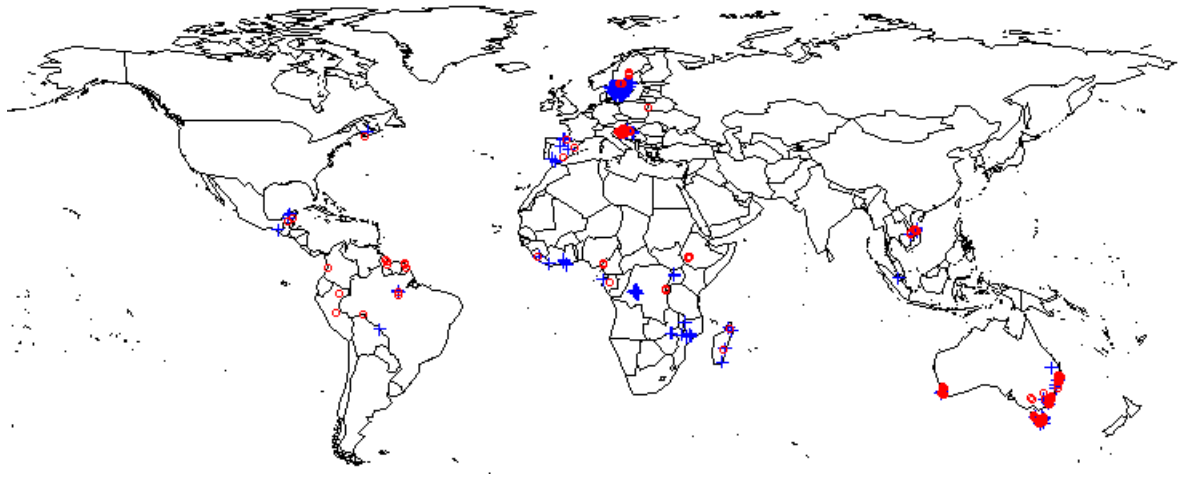


Figure 20. Locations of 0.1° cells with the most extreme differences between residuals in the 2010 and 2018 AGB products (2010 – 2018). The 5% cells with the most negative differences (i.e., 2018 > 2010) are indicated in red whilst the 5% largest positive differences (i.e., 2018 < 2010) are shown in blue.

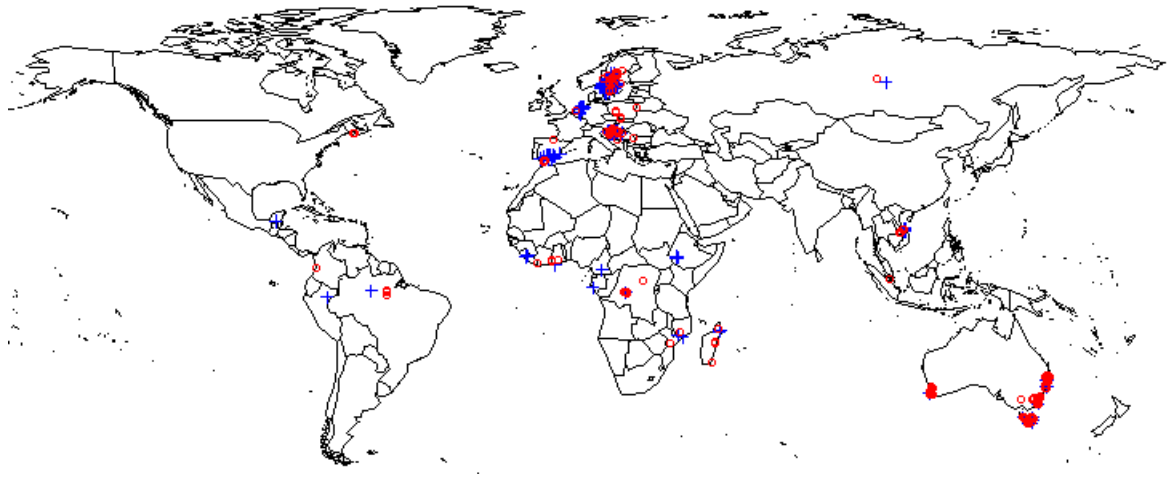


Figure 21. Locations of 0.1° cells with the most extreme differences between residuals in the 2017 and 2018 AGB products (2017 – 2018). The 5% cells with the most negative differences (i.e., 2018 > 2017) are indicated in red whilst the 5% largest positive differences (i.e., 2018 < 2017) are shown in blue.

Comparison of current maps with previous 2018 AGB product

The global AGB_{map} - AGB_{ref} comparisons spatially aggregated to 0.1° and binned over 25 Mg/ha wide AGB ranges for CCI Biomass in 2018 (Figure 23) exhibits underestimation in the Version 7 compared to Version 6. As previously mentioned, the underestimation above 300 Mg ha $^{-1}$ arises from a set of plots in southern Australia, where the current map estimates are reduced (not shown here). The Version 7 map shows less variability (shorter inter-quartile range) especially in >120 Mg/ha bins.

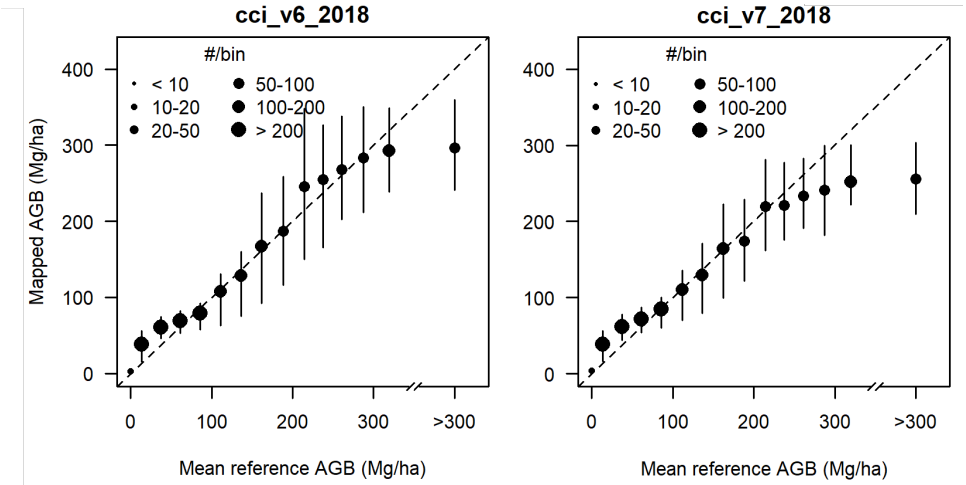


Figure 22. Global AGB_{map} - AGB_{ref} comparisons for 2018 Version 6 and 7 based on inverse variance weighted Tier 1-3 plot data spatially aggregated to 0.1° cells.

Comparison of the CCI maps with other AGB products

Figure 24 shows the global AGB_{map} - AGB_{ref} comparisons spatially aggregated to 0.1° using Tier 1-3 data and binned over 25 Mg/ha wide AGB ranges for the CCI 2020 map and other AGB products. Comparison with the 2020 JPL AGB map (Xu *et al*. 2021) is in the left plot and with the 2020 AGB GEDI map on the right (Duncanson *et al*. 2022). Both show the non-CCI maps have higher underestimation >300 Mg/ha. The GEDI map needed reprojection into WGS 84 and resamping from 0.001° to 0.1° using the average of all pixels. The JPL map by default has a spatial resolution of 0.1° so no pre-processing was needed.

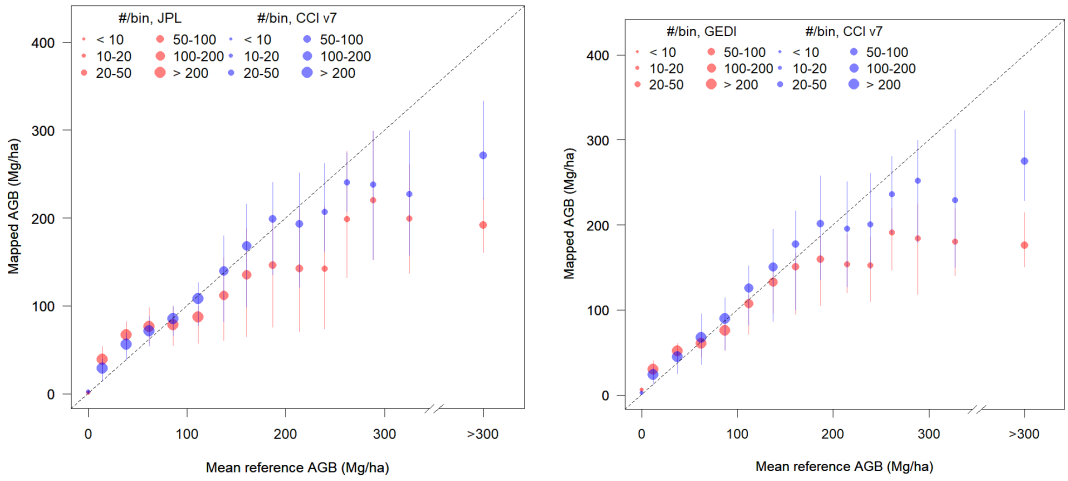


Figure 23. Global AGBmap - AGBref inter-comparisons with other AGB products based on inverse variance weighted Tier 1-3 plot data spatially aggregated to 0.1° cells.

Figure 25 shows the global AGB_{map} - AGB_{ref} comparisons spatially aggregated to 0.1° using LiDAR data and binned over 25 Mg/ha wide AGB ranges for the CCI 2020 map, GEDI 2020 map and the JPL 2020 map. The comparisons between AGB_{map} and AGB_{ref} among the maps show that CCI having higher overestimation until 300 Mg/ha while the other two maps started underestimating >200 Mg/ha. .

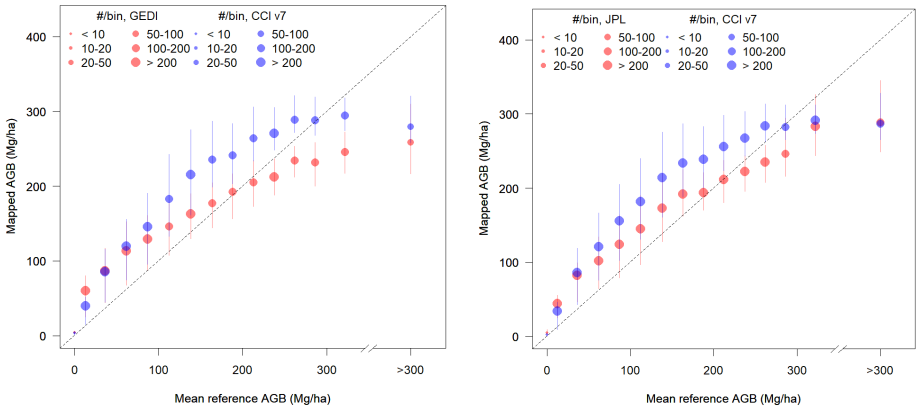


Figure 24. Global AGBmap - AGBref inter-comparisons with other AGB products based on inverse variance weighted LiDAR data spatially aggregated to 0.1° cells.

Comparison among AGB products based on publication year and versions

The figure shows how closely different biomass maps agree with the reference AGB data across biomass ranges. The intercomparison shows a clear improvement in agreement with the reference data from older to more recent biomass maps. Earlier products tend to deviate more strongly from the 1:1 line, especially at higher biomass ranges, whereas newer maps generally track the reference values more closely and more consistently across bins. The versioning comparison also indicates that the latest versions perform better than their previous counterparts.

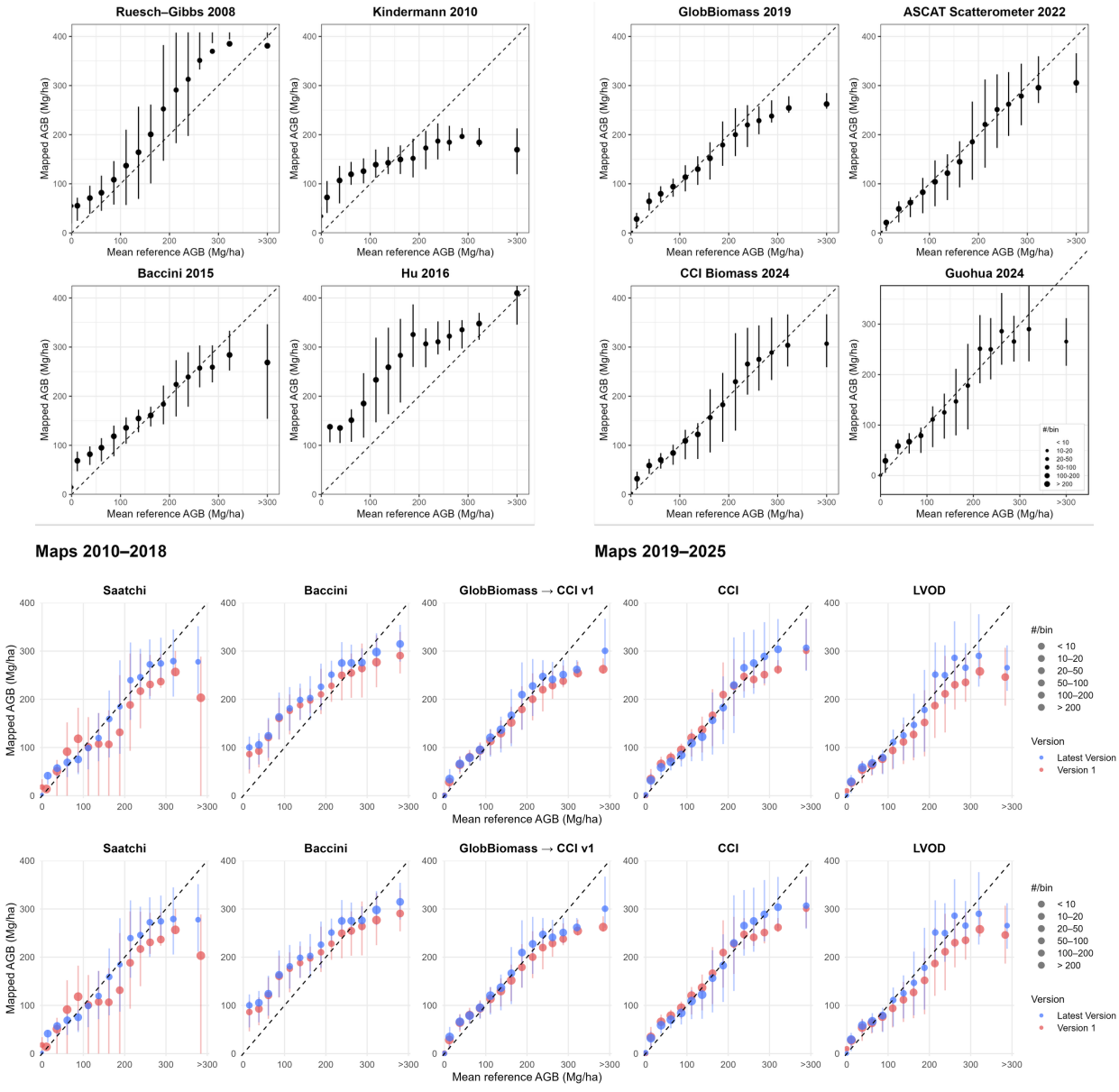


Figure 25. Intercomparison of global aboveground biomass maps against reference AGB across biomass bins, showing (a) older to newer map generations and (b) versioning effects between earlier and latest product releases.

3.8. Within-pixel sampling error

Using the forest-only LiDAR-derived AGB data from forest sites in Remningstorp, Sweden (Ulander *et al.*, 2011), and Lope, Gabon (Hajnsek *et al.*, 2017), the variograms shown in Figure 27 were estimated. The Remningstorp variogram was modelled by two exponential structures with partial sills of 3579 and 1899 Mg^2 ha^{-2} and range parameters of 95 and 531 m, respectively. The Lope variogram was modelled by a 4053 Mg^2 ha^{-2} nugget and a single exponential structure with partial sill of 10553 Mg^2 ha^{-2} and a range parameter of 85 m. Note that the effective range of an exponential variogram is approximately three times the range parameter.

Not surprisingly, the tropical high biomass Lope site has much larger short-range spatial variation than the boreal Remningstorp site (note the different scales on the y-axes). This analysis is part of the previous PVIR .

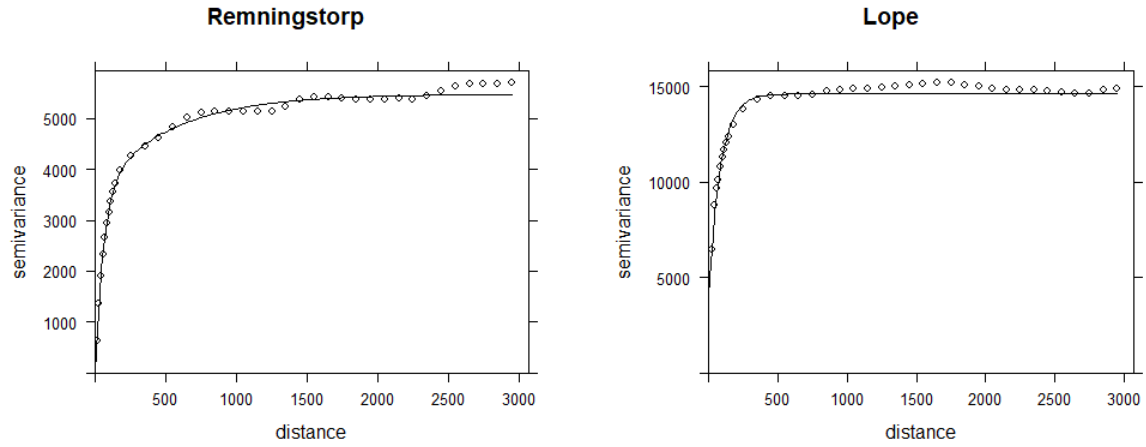


Figure 26. Variograms for the Remningstorp and Lope forest sites. Open dots indicate the experimental variogram and the solid lines represent the fitted models.

Based on the variograms, and assuming single plots with the size of the LiDAR footprints (i.e., 0.01 ha for Remningstorp and 0.04 ha for Lope) centred in 1 ha AGB map pixels, the variance of the plots was found to be 1421 and 6714 Mg^2 ha^{-2} for the two sites. Hence, the standard deviations amount to 38 and 82 Mg/ha, respectively, which is not negligible.

As demonstrated in the PUG (Santoro, 2020), within-pixel sampling error may suggest map bias even if the map provides a perfect representation of mean AGB at 1 ha spatial support. To replicate this issue using a geostatistical approach, Figure 28 shows a scatterplot of 0.04 ha plot AGB values on the x-axis centred and conditioned on 1 ha pixels that are plotted on the y-axis. The pixel values are in the range 10 to 400 Mg/ha and the plot values are drawn from Gaussian populations with mean given by the pixel value and variance and spatial correlation given by the Lope variogram. Any negative value drawn from a Gaussian population was set to zero.

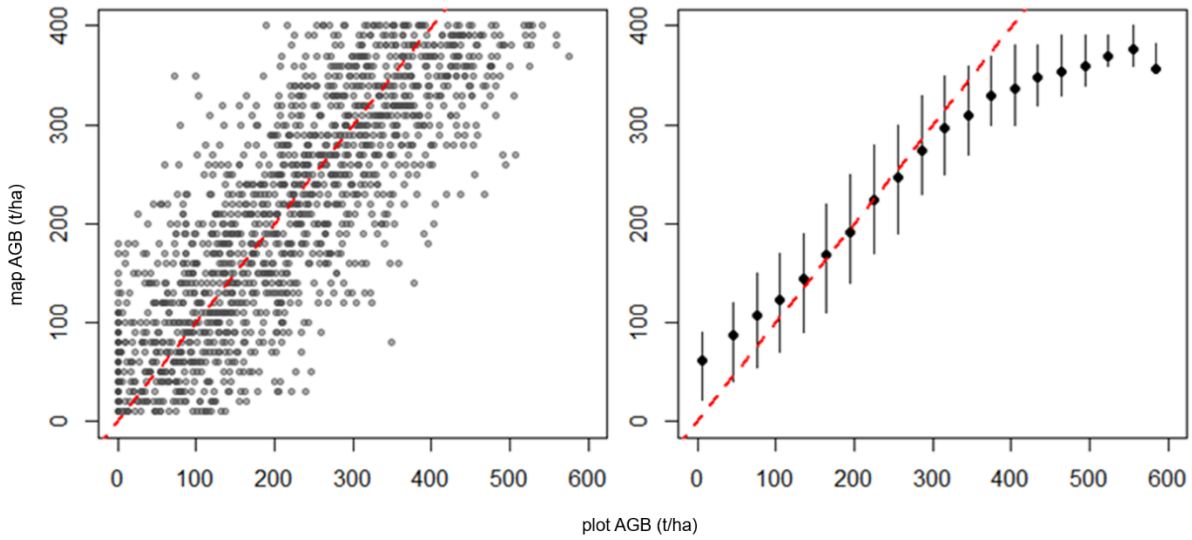


Figure 27. Scatterplot of 0.04 ha plot values conditioned on 1 ha pixel values (left) and binned over 30 Mg/ha wide biomass ranges with dots representing mean AGB and whiskers representing the interquartile range of pixel biomass values for plots inside the bins (right). The dashed red lines are 1:1 lines.

The scatterplot and the interquartile whisker plot in Figure 28 suggest the pixel overestimates low AGB and underestimates high AGB at plot level. However, the plot data were conditioned on the pixel data. Therefore, the observed effect is entirely due to the within-pixel sampling error.

The above effect reduces substantially if multiple plots are used to represent a pixel. To demonstrate this, the above experiment was repeated with five plots regularly spread over the pixel. In Figure 29, the means of the AGB from five plots are on the x-axis, while the conditioning pixel values are on the y-axis. In this figure, the bias observed in Figure 28 is mostly absent, except for the far ends of the AGB range.

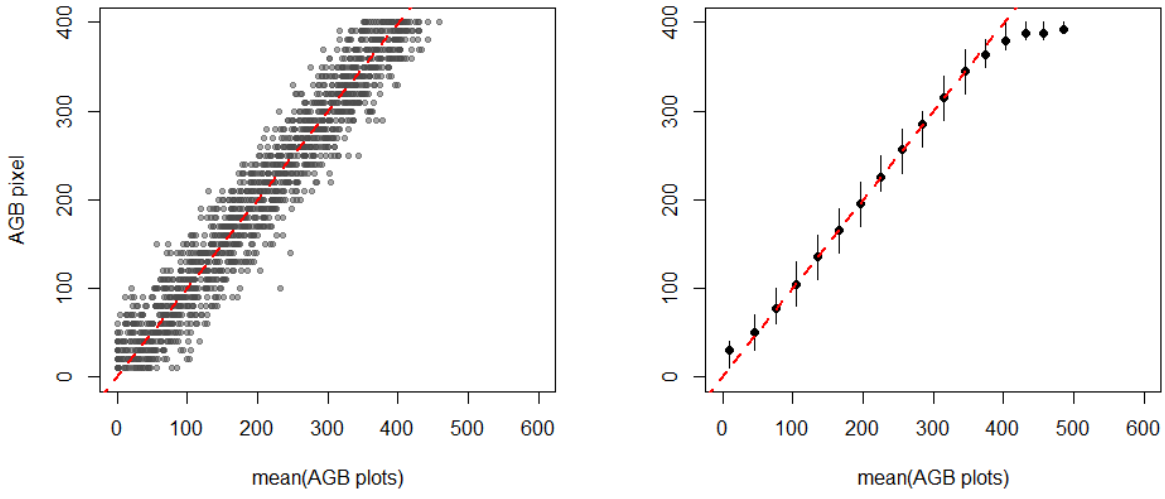


Figure 28. Scatterplot of the mean of 0.04 ha plot values conditioned on 1 ha pixel values (left) and binned over 30 Mg/ha wide biomass ranges with dots representing mean AGB and whiskers representing the interquartile range of pixel AGB values (right). The dashed red lines are 1:1 lines.

The reasons for including this section in the PVIR are: (1) to corroborate the experiment shown in the PUG (Santoro, 2020) and (2) to demonstrate a method for diagnosing the within-pixel sampling error and show the importance of taking it into account when validating map pixels with data from small plots. For the latter, we need variography for the different environmental circumstances

(e.g., biomes), which can be obtained from small footprint (0.01-0.04 ha) LiDAR-derived AGB data, such as the data used in this section. Currently, we have such data only for a single boreal forest site and one site in a tropical forest. More data in these biomes as well as other biomes are needed to routinely account for the within-pixel sampling variance in AGB_{map} – AGB_{ref} comparisons.

3.9. Next steps

For the upcoming map validation exercises, the following needs to be prioritized:

- Continuous updating of the reference database to include additional years e.g., AGBref database (Araza *et al*. under revision)
- Scope a concept for collecting and comparing reference and map-based estimates for biomass change
- Use of country forest masks for user-led validation in Section 3.6, i.e. detailed 10 m resolution maps of land cover and semi-natural habitats in Wales.
- Revisit of certain biomass allometric models used in Appendix A, e.g. for AUS1.

Conclusions

Fully reported and transparent validation is important for increasing the acceptance of satellite-derived products in the user community. To assess the accuracy of the AGB estimates of the new 2007-2012, 2015-2024 CCI Biomass global AGB maps, AGB predictions were compared with independent plot data, LiDAR-based AGB estimates and CoFor and EMAP data, which were used as reference data.

The plot data were adjusted for temporal discrepancies and partial forest fraction (see PVP). Three tiers of plot data were defined, ranging from a large set of data, depending on the reference year of the AGB map) from small plots (on average 0.15 ha and including small NFI plots), to a small set of data from large (> 6 ha) research plots (21 – 27 plots). The latter Tier 3 data mainly consist of plots in the tropics that, though of high quality, are so few that they barely allow conclusions to be drawn about the quality of the CCI Biomass maps. Tier 2 plots (413 – 655 plots), with an average size of 1 ha, revealed that globally the CCI Biomass maps at their original 1 ha resolution tend to over-predict AGB_{ref} up to 50 Mg/ha and to under-predict AGB_{ref} beyond 350 Mg/ha. For the Tier 1 data, the map under-prediction starts at a reference AGB of approximately 120 Mg/ha. It should be noted that part of the observed underestimation of high AGB and overestimation of low AGB observed for small plots can be attributed to within-pixel sampling error.

Spatial aggregation of plot and map data to 0.1° cells (a level of aggregation suitable for most climate modellers) considerably improved the agreement between AGB_{ref} and AGB_{map}, though over-prediction was still observed in the low AGB range and higher reference AGB was under-predicted. Similar results were obtained with LiDAR-based AGB estimates which suggests their suitability to serve as reference data for assessing global AGB products. The spatial aggregation also led 2010 results to be more consistent with the 2015-2021 result unlike for the non-aggregated results.

In general, between 50 Mg/ha and 400 Mg/ha, mean differences between AGB_{map} and AGB_{ref} were found to be well within 20% of AGB_{ref} at 0.1° cell level. This does not hold for the RMSD, which over the entire AGB range exceeds 20% of AGB_{ref}. Nevertheless, it is concluded that spatial aggregation reduces the effect of localized AGB fluctuations in the map and plot-map geolocation mismatches. The AGB_{map} - AGB_{ref} comparisons at 0.1° resolution differentiated by biome (Dinerstein *et al.*, 2017) produced patterns similar to the global comparison for many biomes and particularly highlighted the confidence in the regional AGB estimations up to 300 Mg/ha for the different tropical forest regions. The correspondence between AGB_{ref} and AGB_{map} was lower for the tropical and subtropical *dry* broadleaf forest biome. Similarly, the AGB_{ref} and AGB_{map} comparisons for tropical and subtropical grassland showed map under-estimation > 40 Mg/ha. Lack of access to a larger set of reference data for these biomes may have affected this finding.

The overall analysis at 0.1° cell level revealed that Version 7 of the CCI Biomass AGB maps provides lower estimates in the high AGB range than previous versions. The 2010 map was also less consistent with AGB_{ref} than the 2015-2021 maps, which can be attributed to the different number of reference data used and also differences in the remote sensing input data of the CCI maps. Comparison with AGB_{ref} data revealed that all maps exhibit underestimation in the high biomass bins..

This PVIR demonstrated a geostatistical method for assessing the variance of within-pixel sampling error using variography derived from small-footprint LiDAR-based AGB estimates from forest sites in Sweden and Gabon. Additional datasets are needed to extend this analysis and use it for error budgeting when using (small) plot data for AGB map assessment.

Acknowledgments

We are grateful to all data contributors (see Appendix A) for providing forest plot data for the independent validation of the CCI Biomass maps. We are also thankful to Forest Research (in conjunction with the European Regional Development Fund/Welsh Government funded Ser Cymru Living Wales project) and the Russian Forest Federal Agency in conjunction with the team of Dmitry Schepaschenko for the user-led independent validation using country data. Acknowledgement is given to Nicolas Labriere for processing the SLB dataset, originally intended for the CCI validation exercise and associated researches.

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Appendix A - Details on the used forest plot data (for updating)

ID	Tier	Average year	Average size (ha)	Count	Biome	URL	Paper/ source	Data access
AFR_L	3	2011	25.00	1	Tropical rainforest	https://dspace.stir.ac.uk/retrieve/74d3b352-fa46-418f-ba95-728bb33f4cfc/08417912.pdf	(Labrière *et al.*, 2018)	open
EU_FOS	3	2014	16.25	1	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
SAM_L	3	2010	7.65	20	Tropical rainforest	https://dspace.stir.ac.uk/retrieve/74d3b352-fa46-418f-ba95-728bb33f4cfc/08417912.pdf	(Labrière *et al.*, 2018)	open
AUS1	3	2009	25.00	1	Tropical dry forest	http://data.auscover.org.au/xwiki/bin/view/Product+pages/Biomass+Plot+Library	(Paul *et al.*, 2016)	source-WUR agreement
SAM_RF	3	2008	5.3	10	Tropical rainforest	http://www.rainfor.org/en/project/about-rainfor	Lopez-Gonzales *et al.*, 2011	Open
AFR_FOS	2	2013	1.00	44	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
AFR_L	2	2016	1.00	56	Tropical rainforest	https://dspace.stir.ac.uk/retrieve/74d3b352-fa46-418f-ba95-728bb33f4cfc/08417912.pdf	(Labrière *et al.*, 2018)	open
AUS_FOS	2	2008	1.00	2	Tropical dry forest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
CAM_FOS	2	2012	1.01	18	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
EU_FOS	2	2010	2.23	2	Boreal coniferous forest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
SAM_FOS	2	2011	1.00	23	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
SAM_L	2	2013	1.04	28	Tropical rainforest	https://dspace.stir.ac.uk/retrieve/74d3b352-fa46-418f-ba95-728bb33f4cfc/08417912.pdf	(Labrière *et al.*, 2018)	open
SAM_BAJ	2	2017	1	3	Tropical rainforest	https://ieeexplore.ieee.org/abstract/document/8518871	Pacheco-Pasccagaza *et al.*, 2020	source-WUR agreement
SAM_RF	2	2008	1	374	Tropical rainforest	http://www.rainfor.org/en/project/about-rainfor	Lopez-Gonzales *et al.*, 2011	Open
UK_FOS	2	2015	1.20	1	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open

AFR10	2	2007	1.00	7	Tropical rainforest	https://iopscience.iop.org/article/10.1088/1748-9326/6/4/049001/meta	(Mitchard *et al.*, 2011)	source-WUR agreement
AFR13	2	2008	1.00	2	Tropical rainforest	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009GL040692	(Mitchard *et al.*, 2009)	source-WUR agreement
AFR14	2	2009	1.63	4	Tropical rainforest	https://www.sciencedirect.com/science/article/abs/pii/S014362281400109X	(Ryan, Berry, & Joshi, 2014)	source-WUR agreement
AFR6	2	2009	1.00	12	Tropical rainforest	https://cbmjour-l.biomedcentral.com/articles/10.1186/1750-0680-9-2	(Willcock *et al.*, 2014)	source-WUR agreement
AFR7	2	2012	1.00	19	Tropical rainforest	https://royalsocietypublishing.org/doi/full/10.1098/rstb.2012.0295	(Lewis *et al.*, 2013)	source-WUR agreement
ASI3	2	2007	1.00	92	Tropical rainforest	https://www.sciencedirect.com/science/article/abs/pii/S0378112711004361	(Morel *et al.*, 2011)	source-WUR agreement
AUS1	2	2012	1.01	63	Subtropical steppe	http://data.auscover.org.au/xwiki/bin/view/Product+pages/Biomass+Plot+Library	(Paul *et al.*, 2016)	source-WUR agreement
SAM2	2	2012	1.00	40	Tropical rainforest	http://geoinfo.cnpm.embrapa.br/geonetwork/srv/ eng/main.home		source-WUR agreement
SAM_FOS	1	2011	0.25	142	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
AFR15	1	2013	0.25	136	Tropical rainforest	https://besjour-ls.onlinelibrary.wiley.com/doi/full/10.1111/1365-2745.12548%4010.1111/%28ISSN%291365-2745.FORESTRY	(Vieilledent *et al.*, 2016)	source-WUR agreement
AFR1	1	2008	0.50	1152	Tropical rainforest	https://agritrop.cirad.fr/572060/1/document_572060.pdf	(Hirsh, Jourget, Feintrenie, Bayol, & Ebaá Atyi, 2013)	source-WUR agreement
AFR10	1	2007	0.50	11	Tropical rainforest	https://iopscience.iop.org/article/10.1088/1748-9326/6/4/049001/meta	(Mitchard *et al.*, 2011)	source-WUR agreement
AFR12	1	2008	0.16	108	Tropical rainforest	https://www.sciencedirect.com/science/article/abs/pii/S0034425711003609	(Avitabile, Baccini, Friedl, & Schmullius, 2012)	source-WUR agreement
AFR13	1	2008	0.50	23	Tropical rainforest	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009GL040692	(Mitchard *et al.*, 2009)	source-WUR agreement
AFR14	1	2009	0.51	70	Tropical dry forest	https://www.sciencedirect.com/science/article/abs/pii/S014362281400109X	(Ryan *et al.*, 2014)	source-WUR agreement
AFR4	1	2012	0.13	110	Tropical mountain system	http://www.geo-informatie.nl/workshops/scw2/papers/deVries.pdf	(DeVries, Avitabile, Kooistra, & Herold, 2012)	source-WUR agreement
AFR5	1	2012	0.08	71	Tropical rainforest	https://pure.mpg.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_2281402	(Vaglio Laurin *et al.*, 2016)	source-WUR agreement

AFR6	1	2009	0.33	12	Tropical dry forest	https://cbmjour-l.biomedcentral.com/articles/10.1186/1750-0680-9-2	(Willcock *et al.*, 2014)	source-WUR agreement
AFR8	1	2008	0.13	105	Tropical moist forest	https://www.sciencedirect.com/science/article/abs/pii/S0034425712001058	(Carreiras, Vasconcelos, & Lucas, 2012)	source-WUR agreement
AFR9	1	2016	0.13	9642	Tropical dry forest	https://www.mdpi.com/2072-4292/5/4/1524 https://fndsmoz.maps.arcgis.com/apps/MapSeries/index.html?appid=6602939f39ad4626a10f87bf6253af1e	(Carreiras *et al.*, 2012)	open, source-WUR agreement
AFR_KEN	1	2011	0.09	362	Tropical and subtropical grasslands, savannas and shrublands			source-WUR agreement
ASI1	1	2008	0.05	2903	Tropical mountain system and rainforest	https://www.tandfonline.com/doi/full/10.1080/17583004.2016.1254009	(Avitabile *et al.*, 2016)	source-WUR agreement
ASI10	1	2008	0.10	1268	Subtropical mountain system	https://www.sciencedirect.com/science/article/abs/pii/S0034425719303608	Zhang *et al.* 2019	source-WUR agreement
ASI2	1	2011	0.11	119	Tropical dry forest	http://www.leafasia.org/sites/default/files/public/resources/WWF-REDD-pres-July-2013-v3.pdf	WWF and OBf, 2013	source-WUR agreement
ASI4	1	2010	0.02	70	Tropical dry forest	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.972.708&rep=rep1&type=pdf	Wijaya *et al.*, 2015	source-WUR agreement
ASI9	1	2012	0.13	74	Tropical rainforest	http://leutra.geogr.uni-je-.de/vgtbRBIS/metadata/start.php	Avitabile *et al.*, 2014	source-WUR agreement
ASI_FOS	1	2014	0.25	2	Tropical rainforest	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open
AUS1	1	2011	0.12	5611	Tropical dry forest	http://data.auscover.org.au/xwiki/bin/view/Product+pages/Biomass+Plot+Library	Paul *et al.* 2016	source-WUR agreement
EU1	1	2011	0.01	16819	Temperate broadleaf and mixed forests and Boreal forests	https://www.slu.se/en/collaborative-centres-and-projects/swedish--tio-l-forest-inventory/	Sweden NFI	source-WUR agreement
EU2	1	2007	0.20	7177	Mediterranean forests	http://www.magrama.gob.es/es/desarrollo-rural/temas/politica-forestal/inventario-cartografia/inventario-forestal--cio-l/	Spain NFI	source-WUR agreement
EU3	1	2013	0.06	3021	Temperate oceanic forest	https://library.wur.nl/WebQuery/wurpubs/454875	Netherlands NFI	source-WUR agreement
EU4	1	2007	0.06	5967	Temperate broadleaf and mixed forests and Mediterranean forests	https://www.agriculturejour-ls.cz/publicFiles/01003.pdf	Cienciela *et al.* 2008	source-WUR agreement
EU_FOS	1	2015	0.28	514	Boreal forests	https://www.-ture.com/articles/s41597-019-0196-1?fbclid=IwAR08vLoOm4xEQo4EUdLtoKsnP6nsNIY5CYnfcoqGcS5Z0_UcyaNIr-jcdDg	(Schepaschenko *et al.*, 2019)	open, source-WUR agreement

NAM1	1	2010	0.04	586	Boreal coniferous forest	https://www.p-s.org/content/112/18/5738.short	Liang *et al.*, 2015	source-WUR agreement
NAM2	1	2004	0.04	75	Temperate mountain system	https://www.nature.com/articles/nature07276	Luyssaert *et al.*, 2008	source-WUR agreement
NAM3	1	2010	0.03	588	Temperate continental forest			source-WUR agreement
NAM4	1	2010	0.04	2794	Temperate mountain system		Alaska NFI	source-WUR agreement
SAM2	1	2013	0.23	241	Tropical rainforest	https://www.paisagenslidar.cnptia.embrapa.br/webgis/	Embrapa, undated	source-WUR agreement
SAM3	1	2011	0.13	111	Tropical rainforest		CIFOR, undated	source-WUR agreement
SAM4	1	2014	0.15	7	Tropical rainforest		CIFOR, undated	source-WUR agreement
SAM5	1	2014	0.60	23	Tropical rainforest		CIFOR, undated	source-WUR agreement
SAM_BAJ	1	2017	0.25	363	Tropical rainforest	https://ieeexplore.ieee.org/abstract/document/8518871	Pacheco-Pasccagaza *et al.*, 2020	source-WUR agreement
SAM_RF	1	2008	1	125	Tropical rainforest	http://www.rainfor.org/en/project/about-rainfor	Lopez-Gonzales *et al.*, 2011	Open
SAM_TAPA	1	2009	0.5	138	Tropical rainforest	https://www.tandfonline.com/doi/full/10.1080/07038992.2014.913477?casa_token=EZxeZoegekkAAAAA%3AZHCN98XtpZRrsS9KoGTBhPy1_yzhAkkLZHfck3fomwSnvSaO7YDiuPV_hne6Mj1Wdn-7ME_sPChP	(Bispo *et al.*, 2014)	source-WUR agreement
AFR_COF	0	2009	100	35029	Tropical moist forest,	https://www.nature.com/articles/s41597-020-0561-0	(Ploton *et al.*, 2020)	open
LIDAR	0	2014	1	744397	Tropical rainforest		SLB, TERN, NEON	Open
LIDAR_SP	0	2017	1	54058	Temperate broadleaf and mixed forests and Mediterranean forests		(Gonzales *et al.*, under preparation)	source-WUR agreement
EU_BEL	1	2013	0.1	688	Temperate broadleaf and mixed forests		Belgium TreeMort	source-WUR agreement
EU_BUL	1	2019	0.1	22	Temperate broadleaf and mixed forests		Dmitrov *et al.*, under preparation	source-WUR agreement

EU_CZR	1	2014	0.1	25	Temperate conifer forests	https://www.sciencedirect.com/science/article/pii/S0925857416307182 https://www.mdpi.com/1999-4907/11/3/268	Brovkina *et al.*, 2017; Novotny *et al.*, 2020	source-WUR agreement
AFR_GHA	1	2010	0.1	94	Tropical rainforest	https://www.sciencedirect.com/science/article/pii/S0378112720310057	Brown *et al.*, 2020	source-WUR agreement
EU_WLS	1	2016	0.5	134	Temperate broadleaf and mixed forests	https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/	Wales NFI	source-WUR agreement
ASI_ind	2	2015	0.5	420	Tropical rainforest		Kumar *et al*. 2023	source-WUR agreement
ASI_nep	2	2015	0.5	2004	Tropical mountainous forest		Khanal *et al*. 2023	open
LIDAR_JUNI	0	2016	1	132405	Temperate woodlands		Campbell *et al*. 2023	source-WUR agreement
LIDAR_LVIS	0	2016	1	148051	Boreal forest	https://lvis.gsfc.nasa.gov/Data/Maps/ABoVE2017Map.html	Zhao *et al*. 2022	Open
EU_FOS	1	2016	0.2	264	Different biomes		(Schepaschenko *et al.*, 2019)	source-WUR agreement
SAM_guy	1	2019	0.1	473	Tropical rainforest		Sukhadeo et l. / Guyana NFI	source-WUR agreement
NAM_TUND	0	2012	0.3	222	Tundra		Open	
ASI_IND	1	2018	0.5	412	Tropical and subtropical dry broadleaf forest		source-WUR agreement	
ASI_NEP1	1	2022	0.1	2009	Temperate broadleaf and mixed forests		source-WUR agreement	
ASI_NEP2	1	2022	0.1	1010	Temperate broadleaf and mixed forests		Open	Khanal *et al*. 2023
NAM_JUNI	0	2022	1	132405	Woodlands		source-WUR agreement	Campbell *et al*. 2024
SAM_KEL	0	2019	1	10000	Tropical rainforest		source-WUR agreement	Ometto *et al*. 2023
ASI_PAK	1	2022	0.1	268	Temperate broadleaf and mixed forests		source-WUR agreement	
ASI_MANG	1	2022	0.1	100	Mangroves		source-WUR agreement	Bilolo *et al*. 2024
ASI_MONG	1	2014-2017	1	4,000	tropical mountainous forest	https://www.fao.org/in-action/boosting-transparency-forest-data/news-and-events/news/detail/strengthening-forest-monitoring--mongolia-publishes-national-forest-inventory/en	Open	
SAM_ECU	1					https://microdata.fao.org/index.php/catalog/2851/pdf-documentation	Open	Open