Toward "optimal" integration of terrestrial biosphere models

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Abstract

Multi-model ensembles (MME) are commonplace in Earth system modeling. Here we perform MME integration using a 10-member ensemble of terrestrial biosphere models (TBMs) from the Multi-scale synthesis and Terrestrial Model Intercomparison Project (MsTMIP). We contrast optimal (skill-based for present-day carbon cycling) versus naïve ("one model – one vote") integration. MsTMIP optimal and naïve mean land sink strength estimates (−1.16 vs. −1.15 Pg C per annum respectively) are statistically indistinguishable. This holds also for grid cell values and extends to gross uptake, biomass, and net ecosystem productivity. TBM skill is similarly indistinguishable. The added complexity of skill-based integration does not materially change MME values. This suggests that carbon metabolism has predictability limits and/or that all models and references are misspecified. Resolving this issue requires addressing specific uncertainty types (initial conditions, structure, references) and a change in model development paradigms currently dominant in the TBM community.

1. Introduction

Multi-model ensembles (MME) are common in Earth system modeling and are routinely generated for model intercomparison projects (MIPs), e.g., CMIP3 [Meehl et al., 2007], C4MIP [Friedlingstein et al., 2006], CMIP5 [Taylor et al., 2012], and ISI-MIP [Warszawski et al., 2013]. Two central challenges associated with MMEs are integration (how individual ensemble members are combined into a single ensemble value) and interpretation (how MMEs inform our understanding of Earth system processes and their uncertainties) [Annan & Hargreaves, 2010; Christensen & Boberg, 2012; Knutti, 2010; Hacker et al., 2011; Stephenson et al., 2012; von Storch & Zwiers, 2013; Zhao et al., 2013]. Integration methods range from "model democracy" or "one model – one vote" where ensemble integration is the mean across all models [Zhao et al., 2013] to linear combinations of ensemble members informed by model error [Eckel & Mass, 2005], degree of independence [Abramowitz & Gupta, 2008; Abramowitz 2010; Masson & Knutti, 2011] or model skill, e.g., Bayesian model averaging [Raftery et al., 2005], reliability ensemble averaging [Giorgi & Mearns, 2002], and "superensembles" [Stefanova & Krishnamurti, 2002]. Regardless of approach, integrated ensembles typically show higher skill than all or most of the ensemble members [Raftery et al., 2008] and are often used as the "best estimate" in climate change assessments [IPCC 2007; IPCC 2010; IPCC 2013].

Ensemble methods may also be used to explore the uncertainty in model simulations that arises from internal variability, boundary conditions, parameter values for a given model structure, or structural uncertainty due to different model formulations [Fisher et al., 2014; Hawkins & Sutton, 2009; Huntzinger et al., 2013; Knutti et al., 2010]. Uncertainty is typically quantified as some measure of spread across the ensemble, e.g., standard deviation. An important consideration here is whether the ensemble is broad enough to represent uncertainty [Annan et al., 2011]. "Broadness" relates to how well the ensemble samples representations of a particular process. As an example, an ensemble that does not represent sub-grid scale cloud formation or the soil moisture-precipitation feedback will not directly inform uncertainty related to these processes.

Traditionally, MME studies have focused primarily on the atmospheric component of Earth system models. This is related to the legacy of numerical weather prediction (NWP), which serves as the basis for the atmospheric component of climate models [Leonardo et al., 2014; Lynch, 2008], and where leveraging ensemble forecasts has a long tradition [e.g., Epstein, 1969].

In contrast, analyses of MME integration and interpretation have received significantly less attention for terrestrial biosphere models (TBMs) –the land component of climate or Earth system models– despite several large-scale model intercomparison projects, e.g., Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) [VEMAP, 1995], Potsdam NPP MIP [Cramer et al., 1999], the North American Carbon Program (NACP) Interim Site [Schwalm et al., 2010] and Regional Syntheses [Huntzinger et al., 2012], the Trends in Net Land–Atmosphere Carbon Exchange (TRENDY) [Piao et al., 2013], and the Multi-scale synthesis and Terrestrial Model Intercomparison Project (MsTMIP) [Huntzinger et al., 2013].

Apart from equal weighting, MME integration generally requires some basis (e.g., model skill, error) to inform a linear combination of ensemble members. However, uncertainties or model error are not routinely available for TBM outputs, e.g., perturbed-physics ensembles are rare [e.g., Booth et al., 2012; Huntingford et al., 2009; Zaehle et al., 2005], and "truth" for TBMs, especially at the coarse spatial resolutions that typify TBM output, is not well constrained. Furthermore, total simulation duration for TBMs (years to centuries) is usually much longer than for NWP (days to weeks), resulting in a longer validation cycle. Despite these ongoing challenges for TBM ensemble integration, there is a clear need to better compare TBMs to each other and other independent estimates of land-atmosphere carbon dynamics to better constrain the past and future evolution of the terrestrial carbon land sink.

In this study we develop a methodology that uses an MME to generate a "best estimate" of land-atmosphere CO_2 flux and its associated uncertainty. Our approach uses 10 state-of-the-art TBM simulations from a model intercomparison study with a prescribed simulation protocol

[Huntzinger et al., 2013; Wei et al., 2014]. The principal goal of this study is to contrast the extent to which an "intelligent" skill-based integration differs from naïve integration. In the following section we describe the model ensemble and its integration with optimal weights derived using model-reference mismatch or benchmarking [Luo et al., 2012]. In section 3 we contrast the naïve case ("one model – one vote") with the optimal case. Lastly, in Section 4 we discuss the implications of our findings and suggestions for future research.

2. Model Ensemble and Integration

The model ensemble is drawn from the Multi-scale synthesis and Terrestrial Model Intercomparison Project [MsTMIP; Huntzinger et al., 2013]. MsTMIP uses a prescribed simulation protocol to isolate structural differences in model output, with driving data, land cover, and steady-state spin-up all standardized across models [Wei et al., 2014]. MsTMIP global monthly model runs span a 110-year period (1901-2010) and use a semi-factorial set of simulations where time-varying climate, CO_2 concentration, land cover, and nitrogen deposition are sequentially "turned on" after steady-state is achieved [Huntzinger et al., 2013]. For this study we use the simulation results from 10 TBMs (Table 1) released under MsTMIP Version 1 [http://nacp.ornl.gov/mstmipdata/mstmip_simulation_results_global_v1.jsp]. Here, simulations have all factors enabled (MsTMIP simulation BG1). For the subset of models that do not include a nitrogen cycle, SG3 runs (which exclude nitrogen deposition but are otherwise identical to BG1) are used.

For model integration, i.e., combining ensemble members to a single integrated value, we contrast two use cases: (i) the ensemble mean where each model is weighted equally (hereafter: naïve case); and (ii) an optimal case where weights are derived using reliability ensemble averaging [REA; Giorgi & Mearns, 2002]. We apply these two use cases to four variables: net ecosystem exchange (NEE, i.e., land sink strength), gross primary productivity (GPP), vegetation biomass, and net ecosystem productivity (NEP). MsTMIP definitions for NEP and NEE are: $NEP = GPP - R_h - R_a$ and $NEE = R_h + R_a + E_{LUC} + P - GPP$, respectively, where R_h is heterotrophic respiration, R_a autotrophic respiration, E_{LUC} emissions from anthropogenic activities (e.g., deforestation, shifting agriculture, biomass burning) that cause land use change [Le Quéré et al., 2013], and P is emissions due to harvested wood product decay.

The weights required for the optimal case are derived using REA. This method uses reference data products and model-reference mismatch [Luo et al., 2012] as well as inter-model spread [Giorgi & Mearns, 2002] to determine model reliability:

$$R_i = \prod_j f_j^{m_j} \quad [1]$$

where R_i is the model reliability factor for model i at a given land grid cell, f_j represents model skill relative to reference factor j, and m_j is a weighting factor. The m_j exponent term gives the relative importance of model skill for each reference factor j [Eum et al., 2012]. In this study, all m_j are initially assumed equal at unity and we calculate reference factors for gross uptake and biomass. We note that while more directly observable quantities (e.g., evapotranspiration per basin or the global residual carbon sink) are available we use gridded references to recovery the spatial morphology of skill and reliability at the scale at which MsTMIP simulations are executed.

For gross uptake we use the global GPP MPI-BGC product based on upscaled FLUXNET data [Beer et al., 2010; Jung et al., 2011]. GPP is the largest global carbon flux [Beer et al., 2010], the dominant carbon input source for terrestrial ecosystems [Chapin et al., 2006], and is important in model benchmarking as TBMs simulate carbon dynamics "downstream" of GPP, i.e., errors in GPP propagate to errors in carbon stocks and other fluxes [Schaefer et al., 2012]. The MPI-BGC GPP dataset is available monthly at 0.5° spatial resolution from 1982 to 2008 and is routinely used in benchmarking [e.g., Anav et al., 2013; Piao et al., 2013]. While the MPI-BGC product also includes NEE (–17.1 ± 4.7 Pg C per annum), it differs markedly from other estimates, e.g., –2.6 ± 0.8 Pg C per annum from the Global Carbon Project [Le Quéré et al., 2013; http://www.globalcarbonproject.org/]. This bias is also present in upscaled ecosystem respiration and is related to processes not well-resolved [Jung et al., 2011] by FLUXNET (e.g., land use change, fire emissions, post-disturbance recovery, export of carbon by biomass harvesting and soil erosion [Regnier et al., 2013], and carbon emissions from reduced carbon species [Ciais et al., 2008]).

The biomass reference is taken from the IPCC Tier-1 vegetation biomass product [Ruesch & Gibbs, 2008]. This product is based on specific biomass (above and belowground) values for 124 carbon zones mapped using geospatial datasets of global land cover, continent, ecofloristic zone, and forest age. On multi-decadal scales vegetation biomass contributes to net land-atmosphere exchange of carbon [Houghton, 2005] and has direct implications for assessing forest deforestation [Keith et al., 2009], especially reductions in emissions from deforestation and forest degradation (REDD) in tropical forests [Gibbs et al., 2007]. This dataset is available for *c.* 2000 on a 10 minute global grid and is regridded using box averaging to 0.5° spatial resolution.

Using these two reference products, we derive, for each grid cell over the 1982-2008 period, seven reference factors (Table S1) used to calculate R_i. These factors are bound by zero and unity, and quantify (i) bias in mean long-term GPP ($f_{B,i}$), (ii) bias in the standard deviation of mean long-term GPP ($f_{\sigma,i}$), (iii) convergence [Giorgi & Mearns, 2002] in simulated GPP ($f_{C,i}$), (iv) bias in GPP trend ($f_{T,i}$), (v) correlation in GPP ($f_{\rho,i}$), (vi) bias in biomass ($f_{\beta,i}$), and (vii) convergence in simulated biomass ($f_{\gamma,i}$). The convergence factors address inter-model spread whereby higher convergence indicates that simulation output is largely insensitive to TBM, i.e., a robust signal is found across the majority of models [Giorgi & Mearns, 2002]. All reference factors (except $f_{\rho,i}$) are based on normalizing uncertainty by the absolute difference between the reference and simulation. Finally, all factors use well-established skill metrics from intercomparison studies [e.g., Cadule et al., 2010; Exbrayat et al., 2013; Fisher et al., 2014; Luo et al., 2012] and address both the distance between simulated and reference values as well as their correlation and variability in time and space.

With each reference factor defined and equal importance Eq. [1] simplifies to:

$$R_i = f_{B,i} \times f_{\sigma,i} \times f_{C,i} \times f_{T,i} \times f_{\rho,i} \times f_{\beta,i} \times f_{\gamma,i} \qquad [2]$$

These R_i values are then normalized to composite model reliability ($\tilde{R}_i$) for each model, i.e., R_i is scaled to sum to unity across all n models in the ensemble ($\sum_{i=1}^{n} \tilde{R}_i = 1$) for each grid cell. These reliabilities, $\tilde{R}_i$, serve as optimal weights for MME integration:

$$\tilde{F} = \sum_i \tilde{R}_i F_i \qquad [3]$$

where F is one of NEE, GPP, vegetation biomass, or NEP for model i, and $\tilde{F}$, optimally-integrated F, is calculated for each vegetated grid cell, i.e., although R_i are derived using GPP and vegetation biomass they are used for all four variables.

To assess uncertainty of the optimal integration we generate 1000 bootstrap replicates by randomly varying the relative importance of each reference factor m_j from zero (i.e., excluded from reliability calculations) to seven (i.e., only factor considered). Uncertainty is given as either a confidence bound (the 2.5th to 97.5th percentiles) or the standard deviation across all bootstrap replicates where each represents an alternative, albeit plausible, optimal integration.

3. Naïve vs. Optimal Cases

For global aggregates the naïve and optimal cases are indistinguishable despite strong spatial variability in composite model reliability (Figure S1) and individual reference factors (Figures S2-S11). Naïve case NEE is estimated as −1.15 vs. −1.16 Pg C per annum for the optimal case; values reference 1982-2008 means. This difference of −0.01 Pg C per annum is small (Figure 1) relative to the uncertainty of optimal integration (1σ across 1000 replicates: 0.09 Pg C per annum) and relative to interannual variability (1σ across 27 global annual values: 1.13 [naïve] vs. 1.02 [optimal] Pg C per annum).

For NEE the lack of significant difference occurs (i) despite variations in components included in simulated NEE (Table 1), (ii) even though the reference flux GPP does not fully constrain NEE, and (iii) despite smaller ranges in GPP and biomass compared to NEE (Table 1): GPP varies by a factor of *c.* 2 (from 99 [ISAM] to 187 [GTEC] Pg C per annum) and biomass a factor of *c.* 2.5 (from 460 [ORCHIDEE-LSCE] to 1138 [BIOME-BGC] Gt C) whereas NEE ranges from +0.24 (a weak source; ISAM) to −3.63 (a strong sink; VISIT) Pg C per annum.

The lack of difference between naïve and optimal cases globally is supported by uniformly small grid cell differences. The uncertainty of the optimal integration is greater than the difference between the cases for 84% of the vegetated land surface (Figure 1). Also, the spatial morphology of both cases shows a high degree of similarity without any region that skews the global integrals; only a weak tendency for slightly larger (albeit statistically insignificant) differences in tropical forests is present (Figure 2). This holds for composite model reliability as well as considering each reference factor singly (Figure S12).

In using TBM skill for GPP and biomass to estimate reliability for NEE we assume model skill is transitive, i.e., skill in the former is relevant for a model's ability to simulate the latter. As a test we evaluate integration differences for GPP and biomass as well. A result in contrast to NEE would violate this assumption. While there are larger magnitude differences between the optimal and naïve case for GPP (128 and 136 Pg C per annum for naïve and optimal respectively) and biomass (681 and 699 Gt C for naïve and optimal respectively), these differences are statistically insignificant relative to the uncertainty of the optimal case (Figure 1).

A key concern in the comparison of naïve and optimal values is the semantic differences in NEE [Hayes et al., 2012]. While all TBMs adhere to the MsTMIP protocol not all TBMs are able to simulate all components of NEE (Table 1). That is, if NEE is indistinguishable across naïve and optimal integration this begs the question if the inclusion/exclusion of relevant NEE components acts in a compensatory manner. Thus, as an additional check on the equivalence of naïve and optimal cases we test the impact of variable NEE semantics directly using NEP. This test is based on using the largest subset of NEE components simulated across the full ensemble. Here, only gross uptake and gross loss are simulated by all TBMs. The disequilibrium between these two fluxes is *per definitionem* NEP. As seen with GPP and biomass, which are also semantically equivalent across models, differences in NEP (5.32 and 5.76 Pg C per annum for naïve and optimal respectively) are statistically insignificant relative to the uncertainty of the optimal case (Figure 1).

Furthermore, the lack of difference in global integrals is, as seen for NEE, supported by the small magnitudes of grid cell difference between cases (Figure 1) and the high degree of similarity in spatial morphology across cases (Figure 2) for NEP, GPP, and biomass. No region skews the global values with only a weak tendency for slightly larger differences in tropical forests, especially for GPP. For NEP, GPP, and biomass the percent of grid cells where the difference between naïve and optimal values is less than the uncertainty of the optimal integration is 87%, 87%, and 86% respectively (Figure 1).

Does that lack of a significant difference in integrated values indicate that the naïve case is "correct"? The naïve case presupposes equal weighting, i.e., "one model – one vote". For composite model reliabilities ($\tilde{R}_i$) this implies weights of unity normalized by the number of ensemble members, i.e., uncertainty bounds derived from the 1000 replicates must contain a global mean $\tilde{R}_i$ of 0.1 for each model. This is the case for 8 of the 10 models; ISAM and ORCHIDEE-LSCE are near-misses where the upper uncertainty bounds are just below this cutoff (0.096 and 0.095 respectively). A similar pattern is seen with model rank, i.e., a one-number assessment of relative skill (Figure S13). Here, model ranks show considerable overlap without any clear indication of "best" or "worst". Furthermore, even when focusing on a single bootstrap replicate a higher rank does not demonstrate that one model is "good" *per se*. As reliabilities do not exceed 0.25 (unity indicates perfect agreement between TBM and references) a higher rank only shows that the predictive skill of a higher ranked model is marginally higher than the next ranked model. Taken together, the equivalence in global model reliabilities and rank strongly imply that the benchmarking and complexity inherent in optimal integration add no value relative to the naïve case.

Collapsing $\tilde{R}_i$ for each grid cell to ranks yields the preferred model (Figure 3). “Preferred” here indicates the highest composite $\tilde{R}_i$. Applying this approach the most skilled TBM is GTEC which is the preferred model for *c.* 23% of the vegetated land surface. However, the preferred model is, as seen for global ranks, highly variable (Figure 3). Depending on reference factor importance, *c.* 75% of all vegetated grid cells have between 4 and 7 different preferred models (Figure 3, inset) with only 33 of 55,457 vegetated grid cells having the same preferred model throughout. Lastly, while there is the suggestion (Figure 3) that some TBMs exhibit higher skill levels, the associated variability emphasizes the equivalence of models (Figure 3, inset). That is, a given TBM only posts higher reliability scores under a particular set of references and relative importance of those reference factors. These conditions are not identifiable *a priori* such that skill-based discrimination is not feasible as the signal (actual model skill) is dwarfed by the noise (plausible approaches to asses actual model skill).

4. Implications

The equivalence of the naïve and optimal cases is a troubling but robust finding of this study. The difference between both integrations is small in magnitude and less than the uncertainty associated with the optimal integration. This holds for global aggregates and is the overwhelmingly dominant pattern on a grid cell basis. Equivalence also applies to both semantically identical (GPP, biomass, and NEP) and semantically diverse (NEE) simulation outputs. Taken together this indicates that TBM skill is largely indistinguishable as well as malleable in that over a plausible set of skill assessments (i.e., the variants in REA from bootstrapping) a model's reliability ranges widely.

To better understand the interplay between TBM skill, ensemble integration, and benchmarking several innovations are needed: As with the atmospheric component of Earth system models, the land component evaluated here must be regularly subject to perturbed-physics ensembles (where parameterizations are varied within some tolerance). This is motivated by parameter tuning [Bindoff et al., 2013; Flato et al., 2013] and the social anchoring tendency of models to regress to the mean value of an existing ensemble or reference [Knuti, 2010; Sanderson & Knutti, 2012]. A systemic exploration of parameter-based divergence in model outputs is needed to quantify and isolate sources of uncertainty and "de-tune" models (i.e., uncover compensatory errors [Collins et al., 2011]). A second innovation concerns steady-state spin-up. Models are routinely run to equilibrium states, where change in carbon stocks is zero within some tolerance [e.g., Huntzinger et al., 2013] prior to actual simulation. However, the resultant initial carbon pool sizes vary dramatically both for fully-coupled Earth system models [Exbrayat et al., 2014] as well as TBMs. For the MsTMIP ensemble evaluated here starting soil carbon pools range from 409 to 2118 relative to a reference value of 890 to 1660 Gt C [Todd-Brown et al., 2013]. Given the interplay between carbon pool size and carbon flux insuring a model's equilibrated state is similar to observations will materially affect TBM skill.

Systemically varying TBM structure [Curry & Webster 2011; McWilliams, 2007] is also a needed innovation. This is especially warranted given the recent emphasis on more comprehensive treatments of Earth climate system dynamics. This additional complexity does not guarantee more accurate projections [Knutti & Sedláček, 2013], but represents another structural component to assess. Here, a change in model building is needed such that discrete subroutines can be altered systematically. Target subroutines must include known problematic processes (e.g., phenology [Richardson et al., 2012], net land use flux [Pongratz et al., 2014], or carbon allocation [De Kauwe et al., 2014]) as well as, in the case of MsTMIP, key processes with uneven (or absent) structural representation [Huntzinger et al., 2014] such as carbon-nitrogen interactions [Zaehle et al., 2014], phosphorous limitation, fire emissions, forest management, and forest age structure. Note that this is a refinement of the prescribed protocol used in MsTMIP which fixes non-structural TBM characteristics but does not guarantee that the ensemble range in structural characteristics equates to a systematic sampling of all possible modeling algorithms.

A further protocol refinement concerns the use of offline runs. While this effectively controls for model-specific implementations of atmospheric coupling it can be considered biased as interactions between the surface energy budget and atmospheric conditions are missing. This suggests a nested experimental design whereby the components of a fully-coupled Earth system model (land, cryosphere, atmosphere, and ocean) are, in conjunction with the semi-factorial base runs, systemically varied. A full factorial design with systematically toggleable subroutines across all Earth system model domains, in turn, requires a deeper understanding of the trade-offs between ensemble size, model complexity, and computational resources [Ferro et al., 2012]. A corollary to this approach is to move model development toward using stochastic treatments of unresolved processes [Palmer et al., 2014] and the realization that treating ensemble spread as uncertainty is an approximation [Curry & Webster, 2011; Parker, 2010].

Another key innovation concerns "ground truth" for gridded model outputs. Here, the analyst must contend with multiple plausible references [e.g., Mitchard et al., 2014; Schwalm et al., 2013] and/or references with large uncertainty bounds [Todd-Brown et al., 2013]. For point-based data upscaled to gridded reference products, like the GPP product used here, representativeness is a further concern [Schwalm et al., 2011]. The resultant ambiguity surrounding "ground truth" can render model reliability a pliable construct. As such we suggest a parallel track of MIPs and DIPs, i.e., data intercomparison projects where "data" encompasses observationally-based reference products. Only when reference datasets themselves have been reconciled and their uncertainty quantified at scales that typify TBM simulations can we unambiguously assess TBM skill. This highlights an advantage of skill-based integration that generalizes to accommodate MIP- and/or DIP-based uncertainties (using χ^2-based metrics [Schwalm et al., 2010]) where available. MIPs and DIPs must also be viewed as necessary vehicles to explicitly link TBM skill gradients to intrinsic model structural characteristics. Effectively mapping uncertainty-aware skill gradients to structural attributes [Schwalm et al., 2010; Xia et al, 2013] has great potential to inform future development of TBMs by identifying subroutines associated with higher skill.

Finally, it is important to emphasize that the TBM equivalence shown here is in the context of carbon metabolism for a given model ensemble with a given set of references. Previous work [Schwalm et al., 2013] showed similar results in model skill assessment using evapotranspiration from fully-coupled CMIP5 runs and we expect this overall result to generalize across multiple land surface processes, especially when "ground truth" is ambiguous. The equivalence between naïve and optimal cases is, however, not a reason to abandon skill-based integration or TBM skill assessment in general. Advancing our understanding across the full taxonomy of uncertainties is necessary to resolve actual model skill as well as issues of MME integration and interpretation. This taxonomy includes uncertainty relative to parameterization, steady-state spin-up (i.e., initial conditions), structure, reference data, and forcing data (relatively well-established in the land surface modeling community [e.g., Barman et al., 2014a,b; Fekete et al., 2004; Haddeland et al., 2011; Jain et al., 2013]).

As is, the enduring popularity of the naïve case is based both on ease (e.g., no references are needed) and the higher skill generally shown by the naïve case relative to most or all ensemble members singly. While it is possible that land surface carbon metabolism has predictability limits similar to atmospheric dynamics [Slingo & Palmer, 2011] –variously termed $\sigma_{climate}$, "irreducible imprecision", or "irreducible ignorance" [McWilliams 2007; Walker et al., 2003]– only a full inventory of uncertainty types will allow an "intelligent" skill-based integration and reveal if TBMs are subject to "reducible ignorance" (where additional insight and predictive skill are achievable [Luo et al., 2014]) or "irreducible ignorance" (where predictive skill is limited).

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Tables

Table 1. Characteristics of terrestrial biosphere models and reference datasets. Native 0.5° spatial resolution for all TBMs. NEE components refer to aspects of biosphere-atmosphere exchange included in NEE: D, maintenance respiration deficit; F, fire emissions; E_{LUC}, land use change emissions; P, product decay emissions. VISIT does not include any of these components. The MsTMIP median model is used for convergence-based reference factors. Carbon fluxes and biomass model values are 1982-2008 global means.

Model	**Run**	**NEE Components**	**NEE [Pg C yr^{-1}]**	**NEP [Pg C yr^{-1}]**	**GPP [Pg C yr^{-1}]**	**Vegetation Biomass [Gt C]**	**Reference**
BIOME-BGC	BG1	F	-0.38	6.46	138	1138	Thornton et al., 2002
CLM	BG1	D/F/E_{LUC}/P	0.16	4.46	142	668	Mao et al., 2012
CLM4VIC	BG1	D/F/E_{LUC}/P	-0.15	3.57	112	550	Lei et al., 2014
DLEM	BG1	E_{LUC}/P	-1.51	2.18	105	475	Tian et al., 2012
GTEC	SG3	P	-2.79	9.67	187	986	King et al., 1997; Ricciuto et al., 2011
ISAM	BG1	E_{LUC}	0.24	1.49	99	642	Jain & Yang, 2005
LPJ	SG3	F/E_{LUC}	-0.53	10.55	138	536	Sitch et al., 2003
ORCHIDEE-LSCE	SG3	E_{LUC}/P	-1.84	6.68	118	460	Krinner et al., 2005
VEGAS2.1	SG3	F/E_{LUC}/P	-1.11	4.48	117	597	Zeng et al., 2005
VISIT	SG3	–	-3.63	3.63	122	763	Ito, 2010
MsTMIP Median	–	–	–	–	120	620	this study
FLUXNET-based GPP	–	–	–	–	119	–	Jung et al., 2011
IPCC Vegetation Biomass	–	–	–	–	–	491	Ruesch & Gibbs, 2008
Naïve Integration	–	–	-1.15	5.32	128	681	this study
Optimal Integration	–	–	-1.16	5.76	136	699	this study

Figures

Figure 1

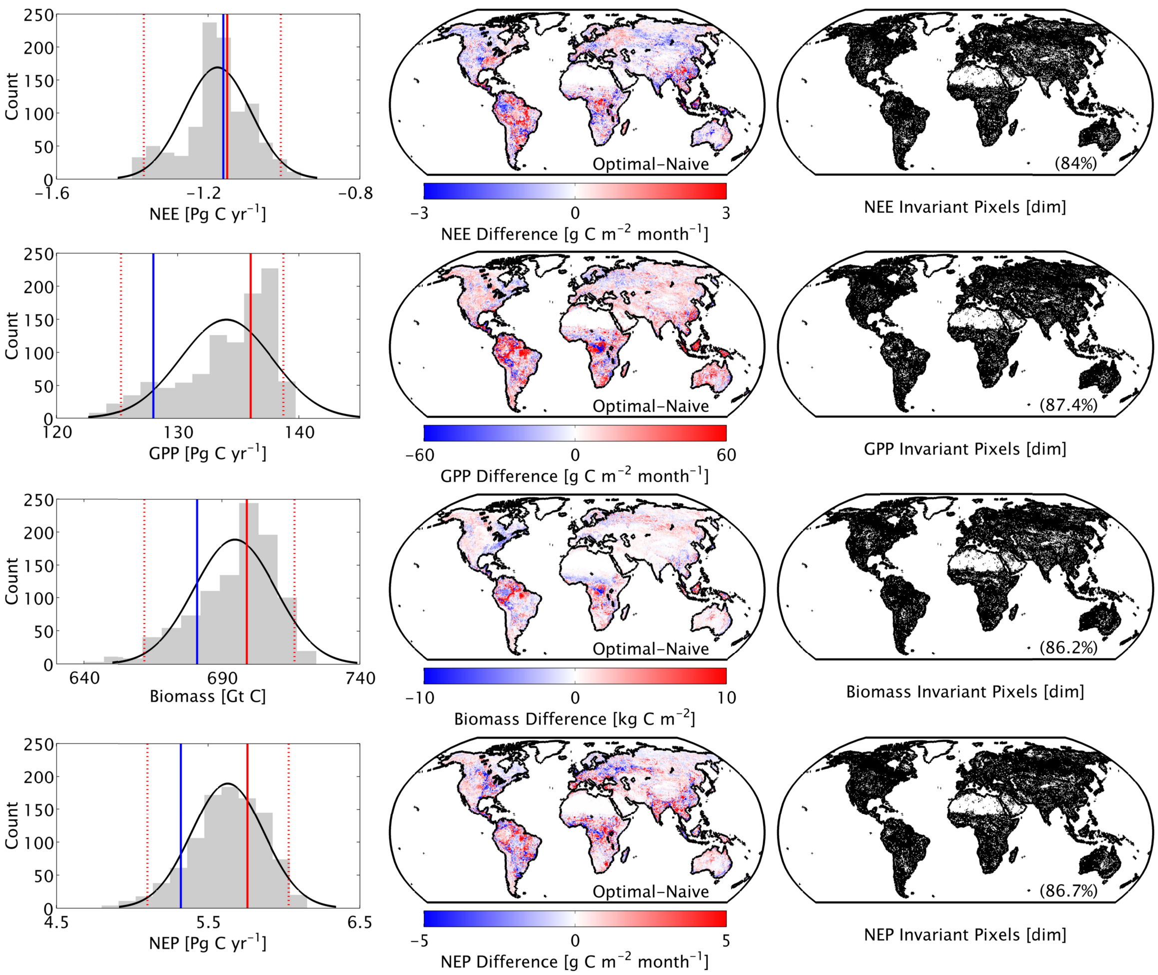


Figure 1. Difference between optimal and naïve cases for NEE, GPP, biomass, and NEP. Left column: histograms (gray), fitted normal distribution (black line), naïve case (blue line), optimal case (dark red line), and optimal case uncertainty bounds (light dashed red lines) for global values. Distributions of optimal case based on 1000 bootstrap replicates with varying reference factor importance. Uncertainty bounds are given by the 2.5th to 97.5th percentiles. Middle column: difference map of optimal and naïve cases. Right column: black grid cells indicate where the naïve is indistinguishable from the optimal case (values in parentheses show percentage of indistinguishable grid cells for the vegetated land surface). All values reference 1982-2008 means.

Figure 2

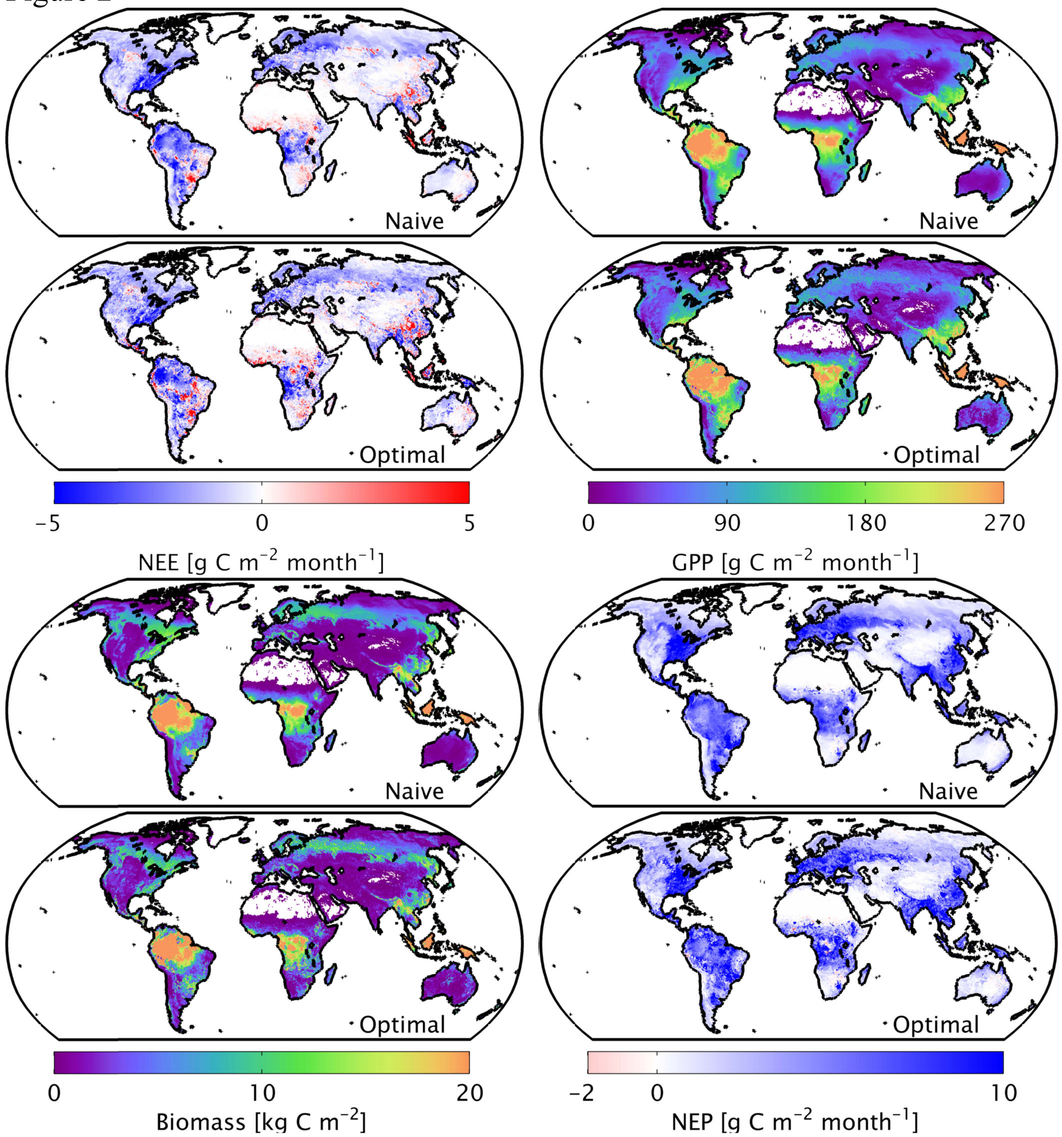


Figure 2. Spatial patterns of naïve and optimal cases. Maps show naïve and optimal case 1982-2008 means for NEE, GPP, biomass, and NEP.

Figure 3

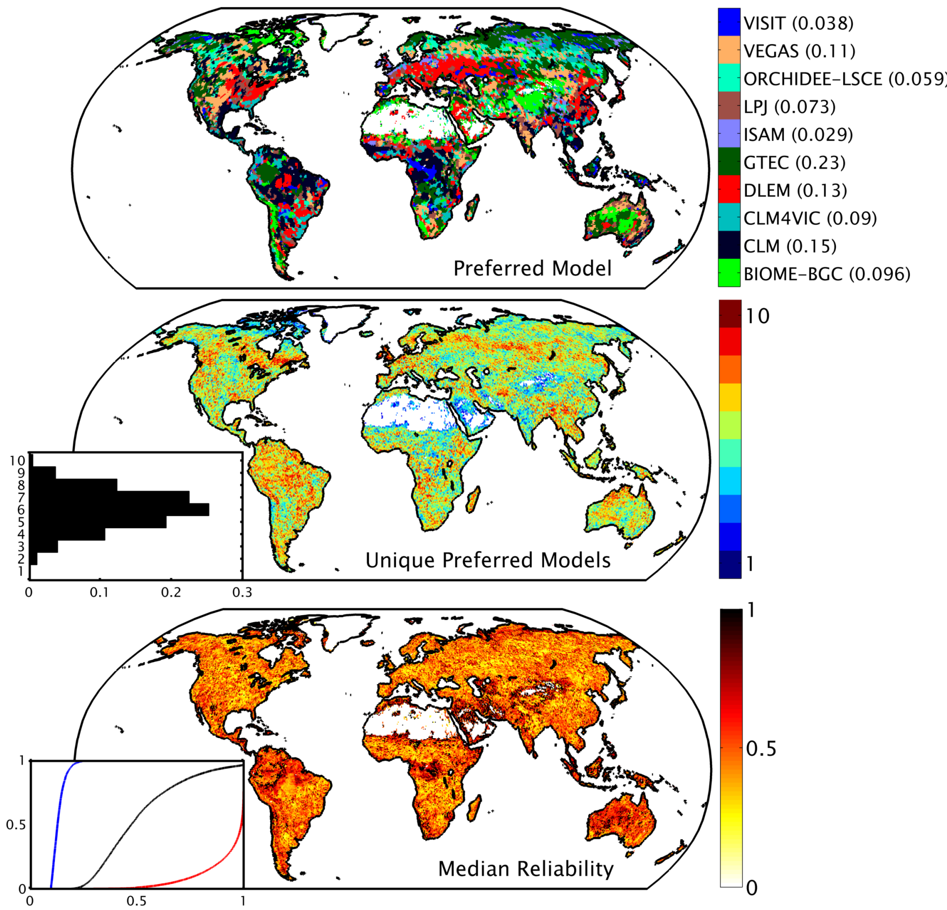
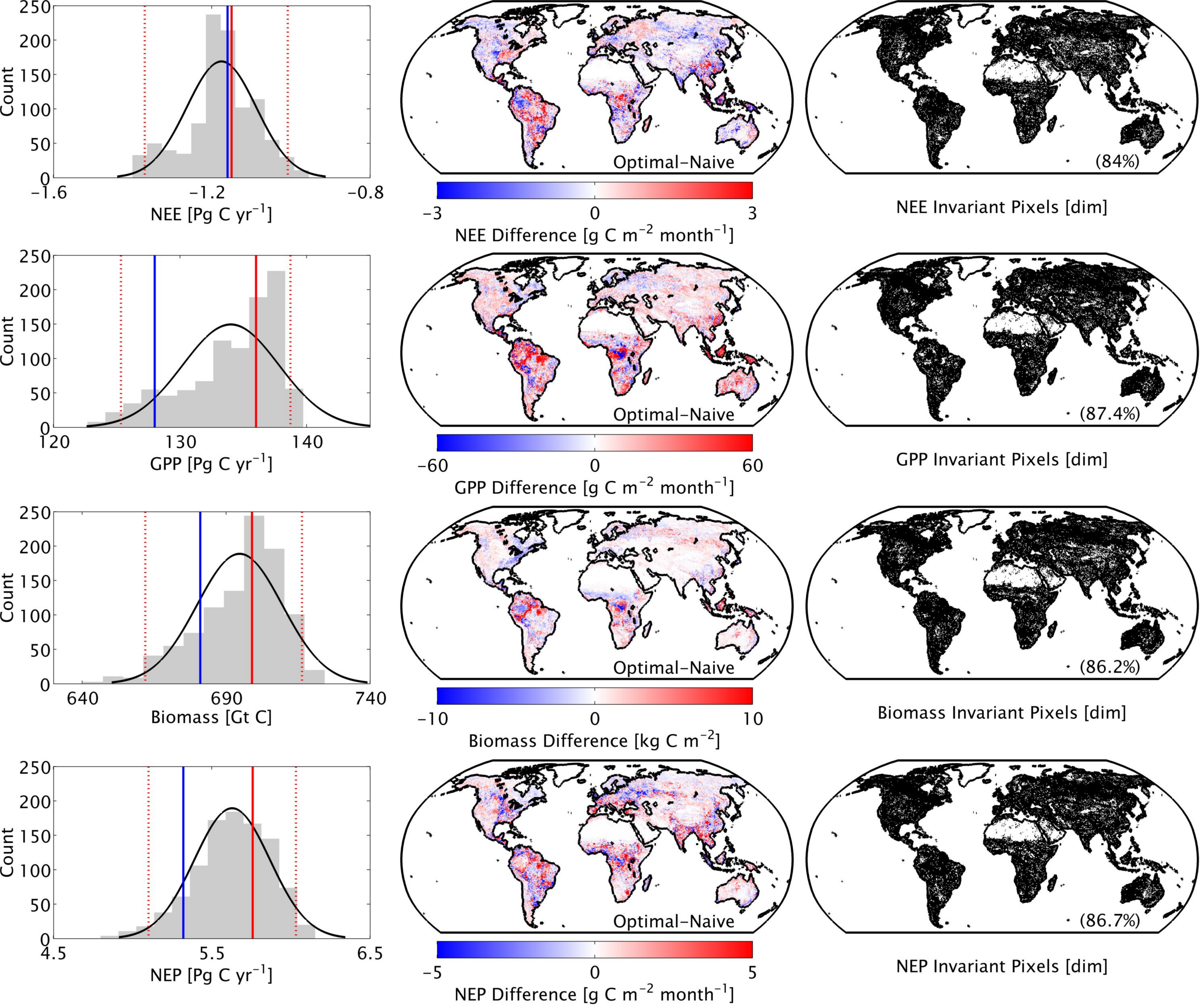
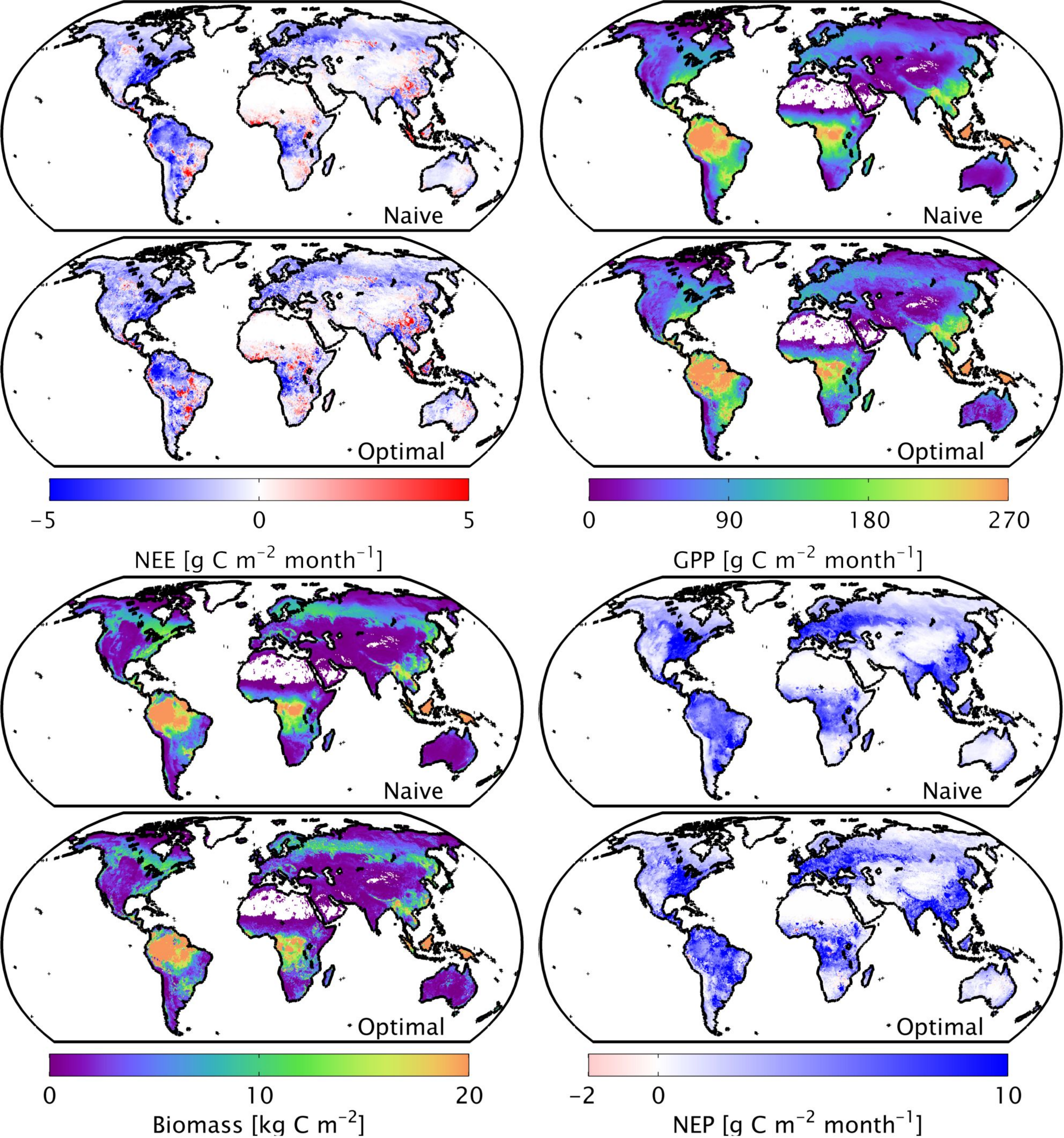
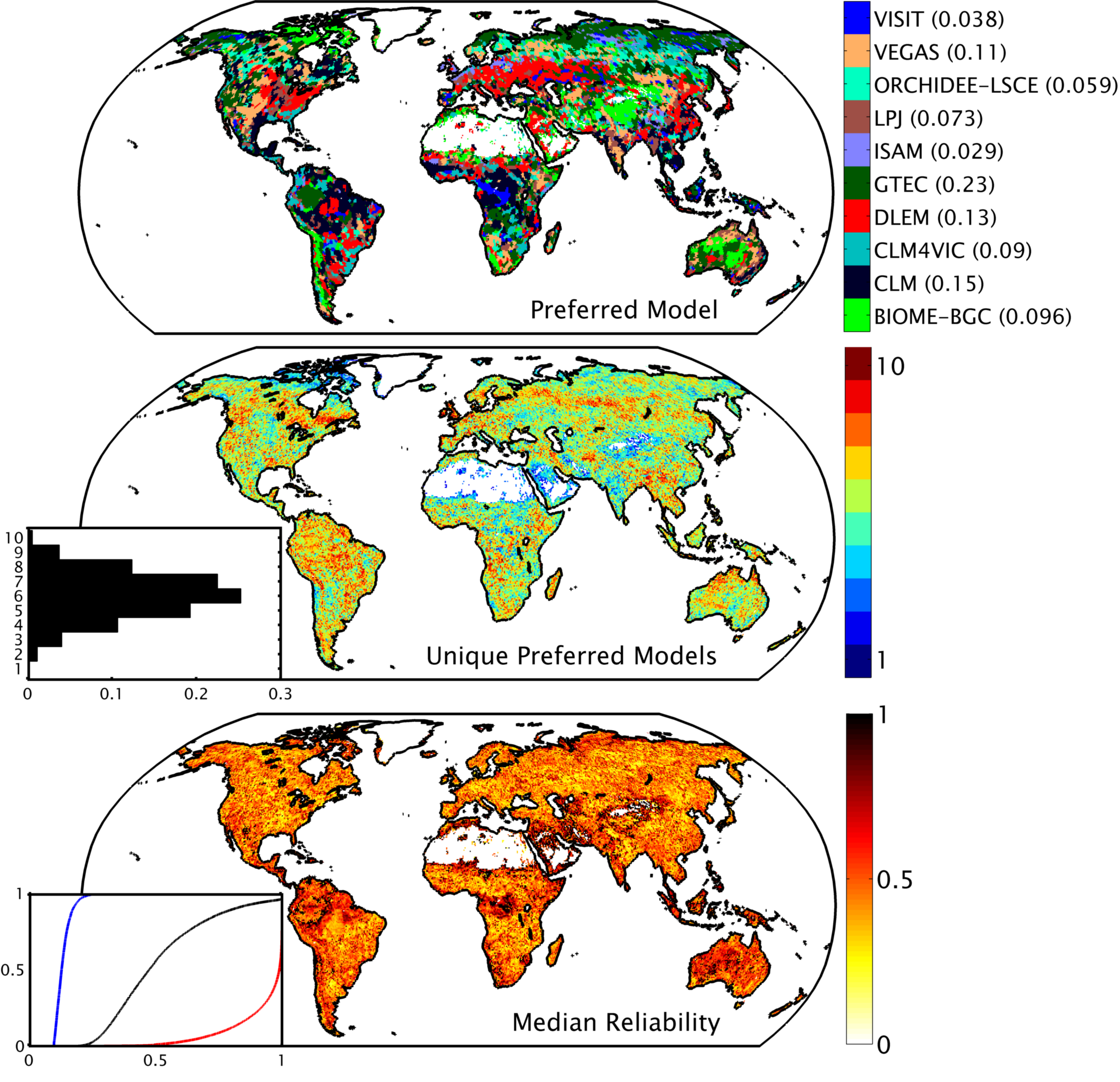


Figure 3. Preferred model. Upper panel: preferred model based on equal relative importance of all seven reference factors, the default optimal case. Values in parenthesis show fraction of vegetated land surface where a given model is preferred. A 3x3 majority filter is used for visualization purposes. Middle panel: number of unique preferred models across all bootstrap replicates, inset shows histogram. Lower panel: median reliability of preferred model across all 1000 bootstrap replicates; inset shows cumulative distribution (y-axis) over maximum (red), median (black), and minimum (blue) reliability (x-axis).



Count
NEE [Pg C yr⁻¹]
Optimal−Naive
NEE Difference [g C m⁻² month⁻¹]
(84%)
NEE Invariant Pixels [dim]
GPP [Pg C yr⁻¹]
GPP Difference [g C m⁻² month⁻¹]
(87.4%)
GPP Invariant Pixels [dim]
Biomass [Gt C]
Biomass Difference [kg C m⁻²]
(86.2%)
Biomass Invariant Pixels [dim]
NEP [Pg C yr⁻¹]
NEP Difference [g C m⁻² month⁻¹]
(86.7%)
NEP Invariant Pixels [dim]


Naive
Naive
Optimal
Optimal
-5
0
5
NEE [g C m^{-2} $month^{-1}$]
0
90
180
270
GPP [g C m^{-2} $month^{-1}$]
Naive
Naive
Optimal
Optimal
0
10
20
Biomass [kg C m^{-2}]
-2
0
10
NEP [g C m^{-2} $month^{-1}$]


VISIT (0.038)
VEGAS (0.11)
ORCHIDEE-LSCE (0.059)
LPJ (0.073)
ISAM (0.029)
GTEC (0.23)
DLEM (0.13)
CLM4VIC (0.09)
CLM (0.15)
BIOME-BGC (0.096)
Preferred Model
Unique Preferred Models
10
9
8
7
6
5
4
3
2
1
0
0.1
0.2
0.3
Median Reliability
0.5
0