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Supplement of

Does predictability of fluxes vary between FLUXNET sites?

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Supplement for: How unique are fluxes from different FLUXNET sites?

Aridity

Arid sites tend to have higher precipitation variability, with fewer, heavier rain events, and longer dry periods (Donat et al., 2016). We would expect that flux predictability would be lower at arid sites. For this hypothesis, we used an aridity index based on mean annual precipitation from CRU TS4.01, and the energy-only estimate for potential evapotranspiration (PET) from Milly and Dunne (2016), based on net radiation and ground heat flux (PET $= 0.8(\overline{Rnet} - \overline{Qg})$) from FLUXNET, such that the aridity index (AI) = mean precipitation/PET. We assumed Qg=0 where sites did not provide Qg (which is approximately true on long time scales).

Figure 1 shows the predictability metrics for aridity index. The pattern shown for each flux, and particularly NEE and Qle, is quite similar to that for mean precipitation in Figure 3 in the paper, with more very arid sites being less predictable.

Extended Budyko Analysis

The following 2 plots show predictability metrics for Potential and Actual evapotranspiration.

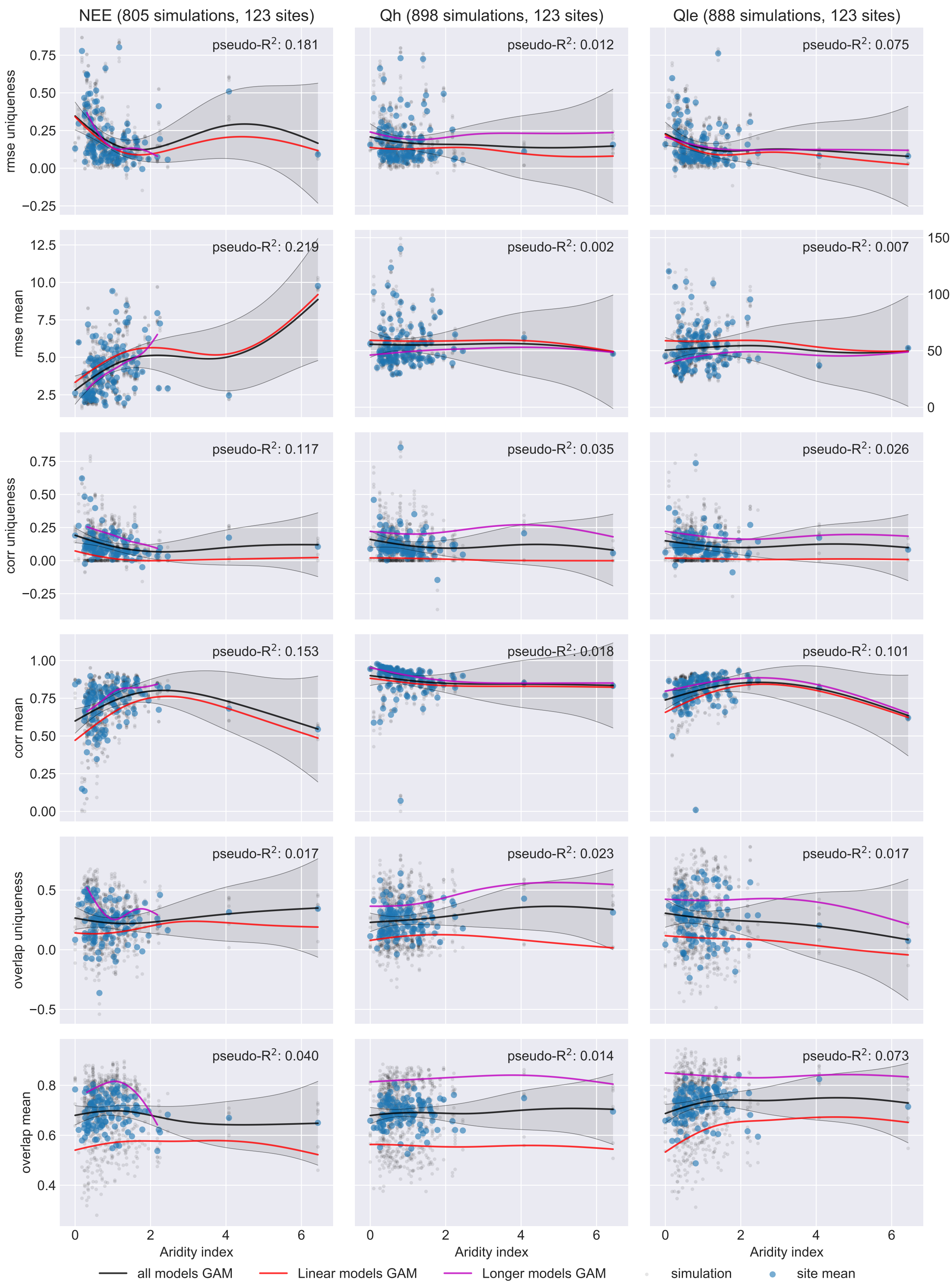
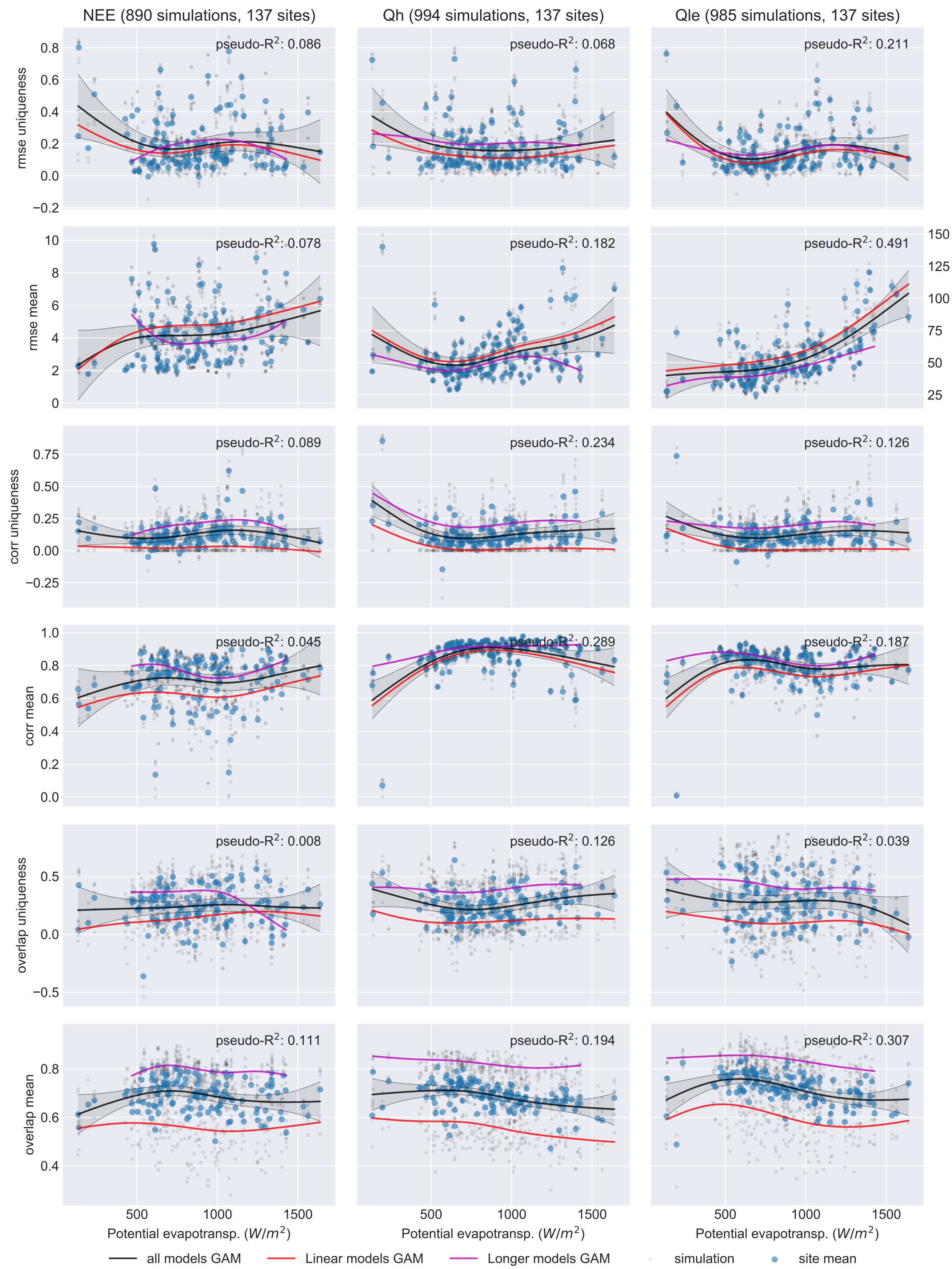
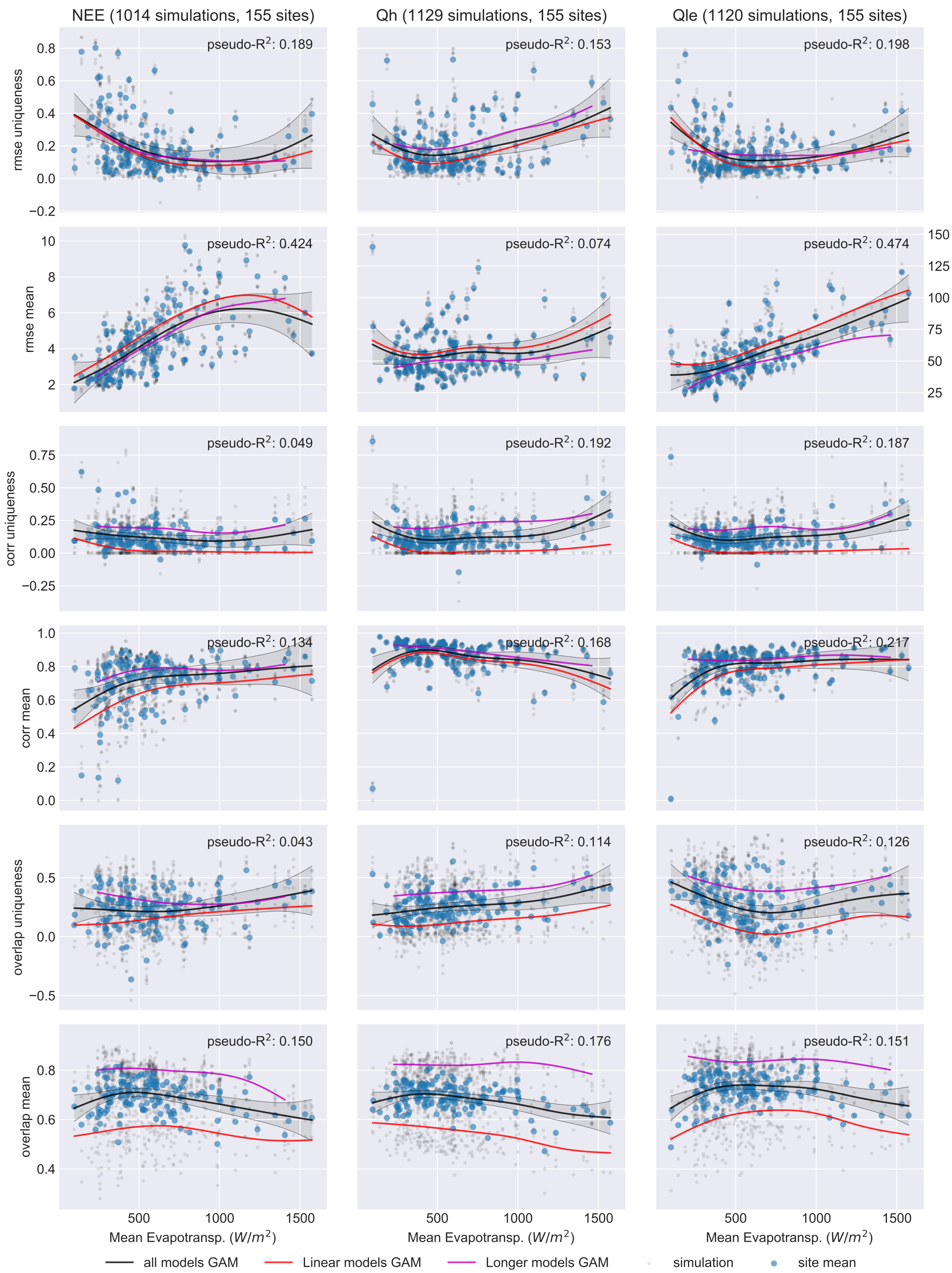


Figure 1: Predictability metrics for Aridity Index. 32 sites failed the Aridity Index calculation.



Predictability metrics for Potential Evapotranspiration (PET).



Predictability metrics for Actual Evapotranspiration.

Predictability as a function of site variability

Interannual variability Sites heavily influenced by longer term climate patterns, such as decadal scale ocean oscillations, are less likely to have all of their relevant patterns captured within the period of FLUXNET measurement, and so potentially contain systematic biases. We compared the interannual variability between sites for both T and P, using the CRU TS4.01 data. We calculated the coefficient of variance (CoV) for annual means of temperature (K), and precipitation (mm/year). We would expect that as IAV increases (shown by greater CoV), predictability would decline.

Seasonality Larger differences between winter and summer conditions would likely lead to lower predictability, since we would expect flux behaviour at such sites to be more diverse over the course of the year. This would also affect the relative influence of time varying factors, e.g. timing of snow melt, or vegetation phenology. For model and site combinations where the training and testing data is more disjointed, this might also lead to lower predictability due to the non-training testing data diverging more in behaviour. Since about 55% of sites in Tier 1 are less than 5 years long, we used the BioClim variables (WorldClim, 2016) to compare seasonality between sites. We investigated: isothermality - the ratio of diurnal temperature range to annual temperature range; temperature seasonality - the standard deviation of monthly average temperatures, normalised by the annual average in K; temperature annual range; precipitation seasonality; precipitation of wettest quarter; and precipitation of the driest quarter.

Diurnal ranges Sites with large diurnal ranges have stronger rates of change between daily peaks and troughs, and these are likely to make prediction harder. Faster changes in temperature, for example, can cause rapid changes in relative humidity, which is a major driver of latent heat flux. We used the BioClim (WorldClim, 2016) mean diurnal temperature range using the nearest neighbouring grid cell for each site.

Results

Variability of forcing variables is a major component in the predictability of fluxes. In general, we might expect higher variability to lead to lower predictability. Here we examine predictability at various time scales. Figure 2 shows the predictability metrics over the interannual variability of temperature, and Figure 3 shows the same for precipitation, using the CRU TS4.01 data. There does not appear to be a strong trend in increased predictability with higher interannual temperature variability Figure 2. However, there does appear to be a clear trend toward higher uniqueness at sites with stronger interannual variability in precipitation for NEE and for Qle (Figure 3).

Other modes of variability descending in scale include intra-annual variability, such as annual range, or variance of monthly values (seasonality); means of particular seasons; and diurnal ranges, as well as mixed-scale measurements, such as isothermality (ratio of diurnal range to annual range of temperature). Measures of each of these for both temperature and precipitation are included in the BioClim data, and plots of uniqueness as a function of each variable are included in the next section. For the majority of cases, there appears to be no clear patterns of note. The exception includes some increase in RMSE uniqueness in NEE, and perhaps also for Qle, for sites with a higher diurnal temperature range (Figure 5).

Extended BioClim plots

The following figures use the WorldClim BioClim variables.

- Figure 5 shows the remaining predictability metrics for diurnal temperature range,
- Figure 6 shows isothermality,
- Figure 7 shows temperature seasonality,
- Figure 8 temperature annual range,
- Figure 9 precipitation seasonality,
- Figure 10 precipitation of wettest quarter, and
- Figure 11 precipitation of the driest quarter.

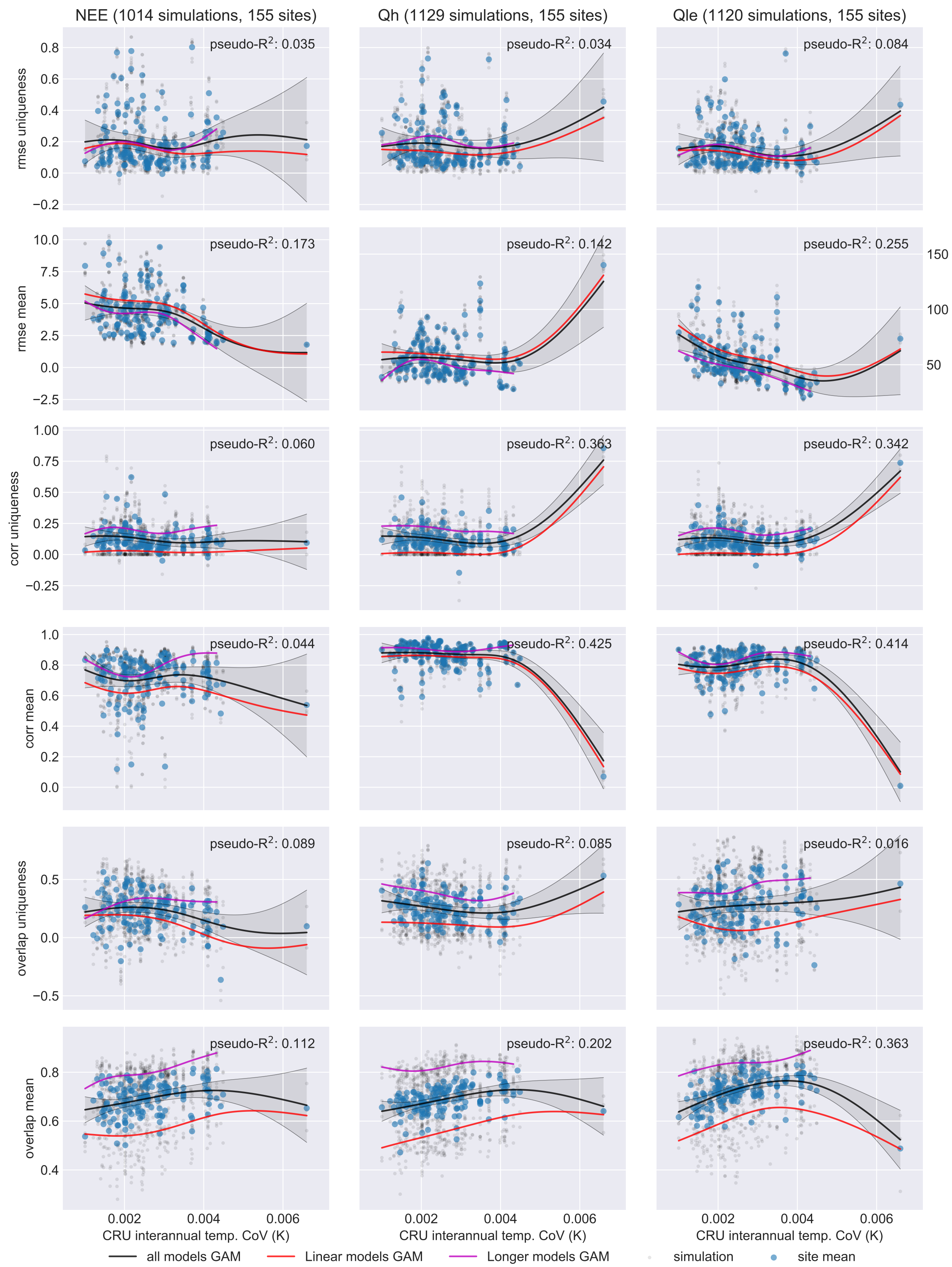


Figure 2: RMSE predictability by temperature interannual variability, calculated from the coefficient of variation in the CRU TS4.01 annual means.

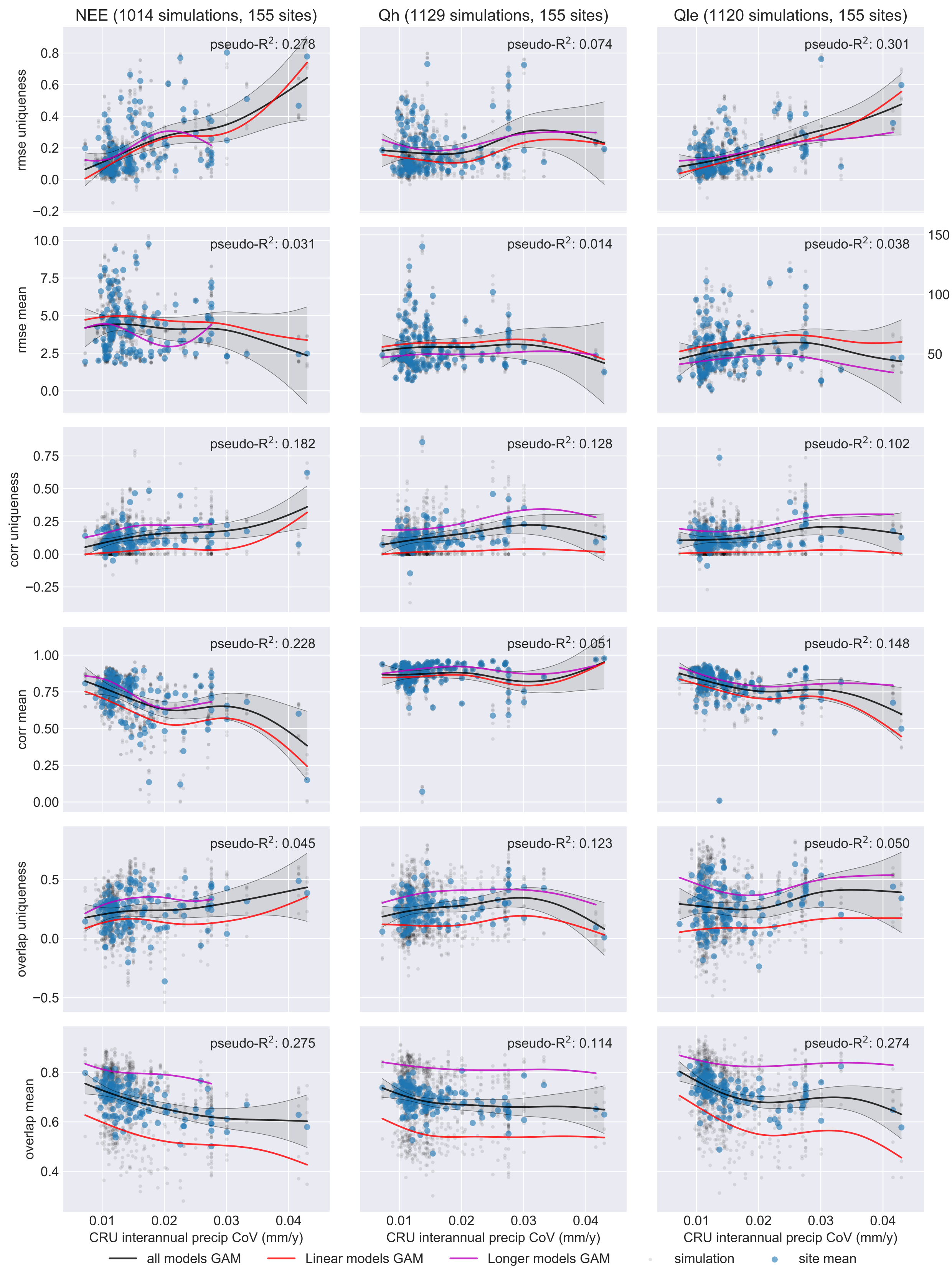


Figure 3: RMSE predictability by precipitation interannual variability, calculated from the coefficient of variation in the CRU TS4.01 annual means.

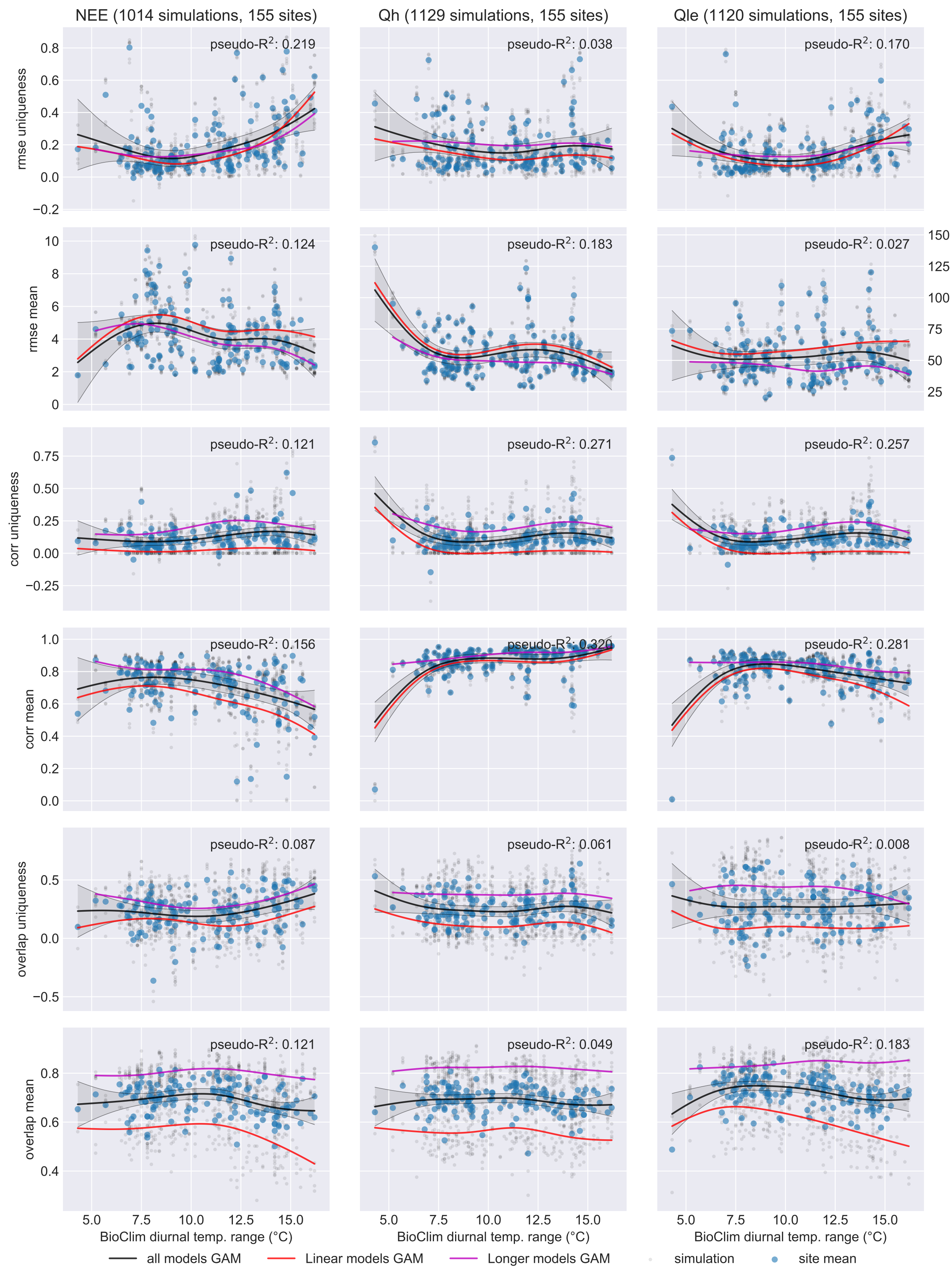


Figure 4: predictability metrics for temperature diurnal range. Note that higher diurnal temperature ranges are likely partially correlated with lower mean precipitation/humidity.

There is a hint of a trend towards higher uniqueness in sites that are driest in their wettest quarter, which is perhaps simply a reflection of the same effect seen in Figure 3 in the paper. Other determinants do not have a clear patterns in predictability.

There are some other patterns visible in some of the other predictability metrics, for example there appears to be a trend towards a better overlap metric at sites with a higher BioClim_t_annual_range, as well as sites with a higher BioClim_t_seasonality.

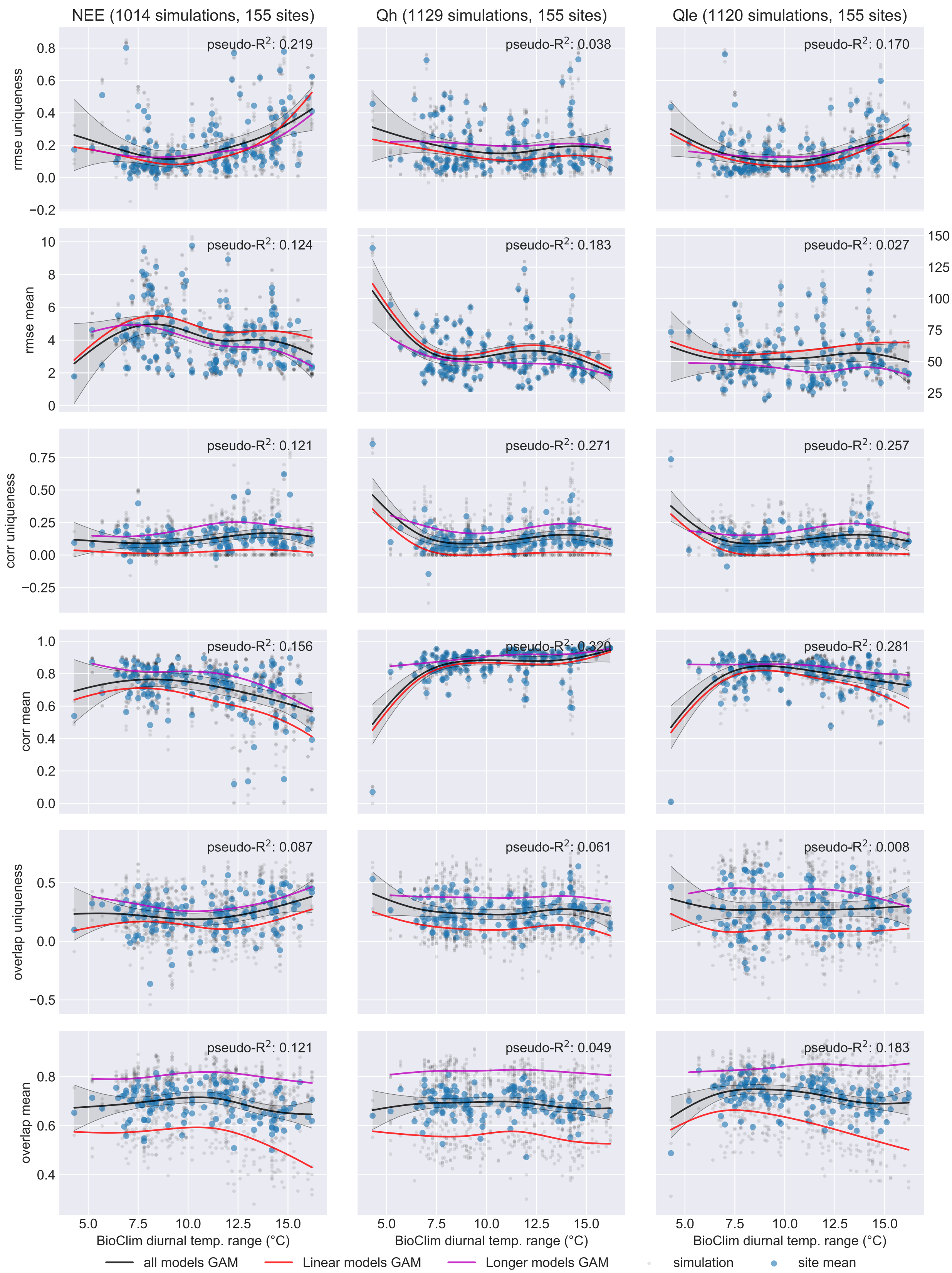


Figure 5: Predictability metrics for temperature diurnal range. Note: The first row is already included in the paper.

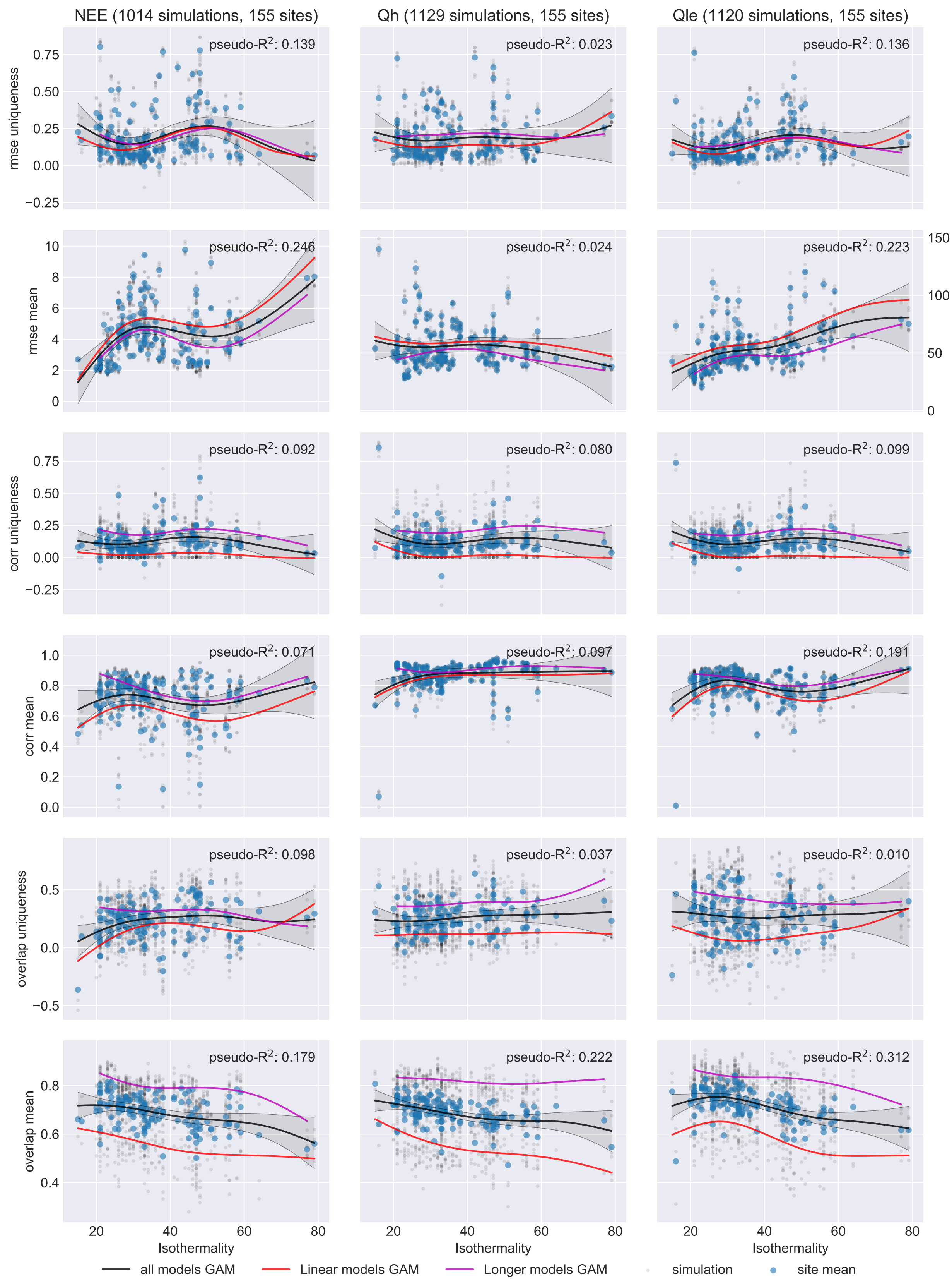


Figure 6: Predictability metrics for temperature isothermality.

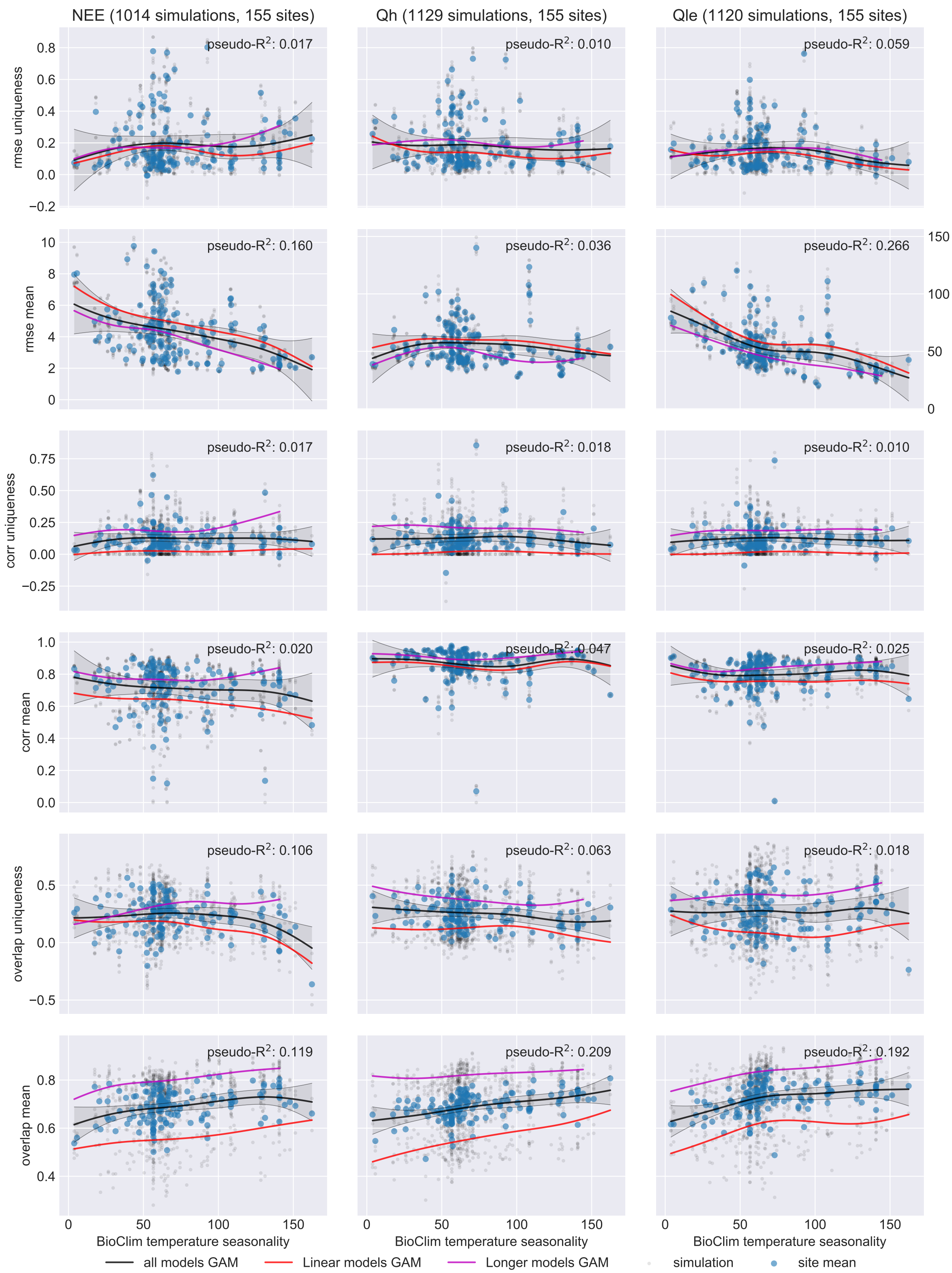


Figure 7: Predictability metrics for temperature seasonality.

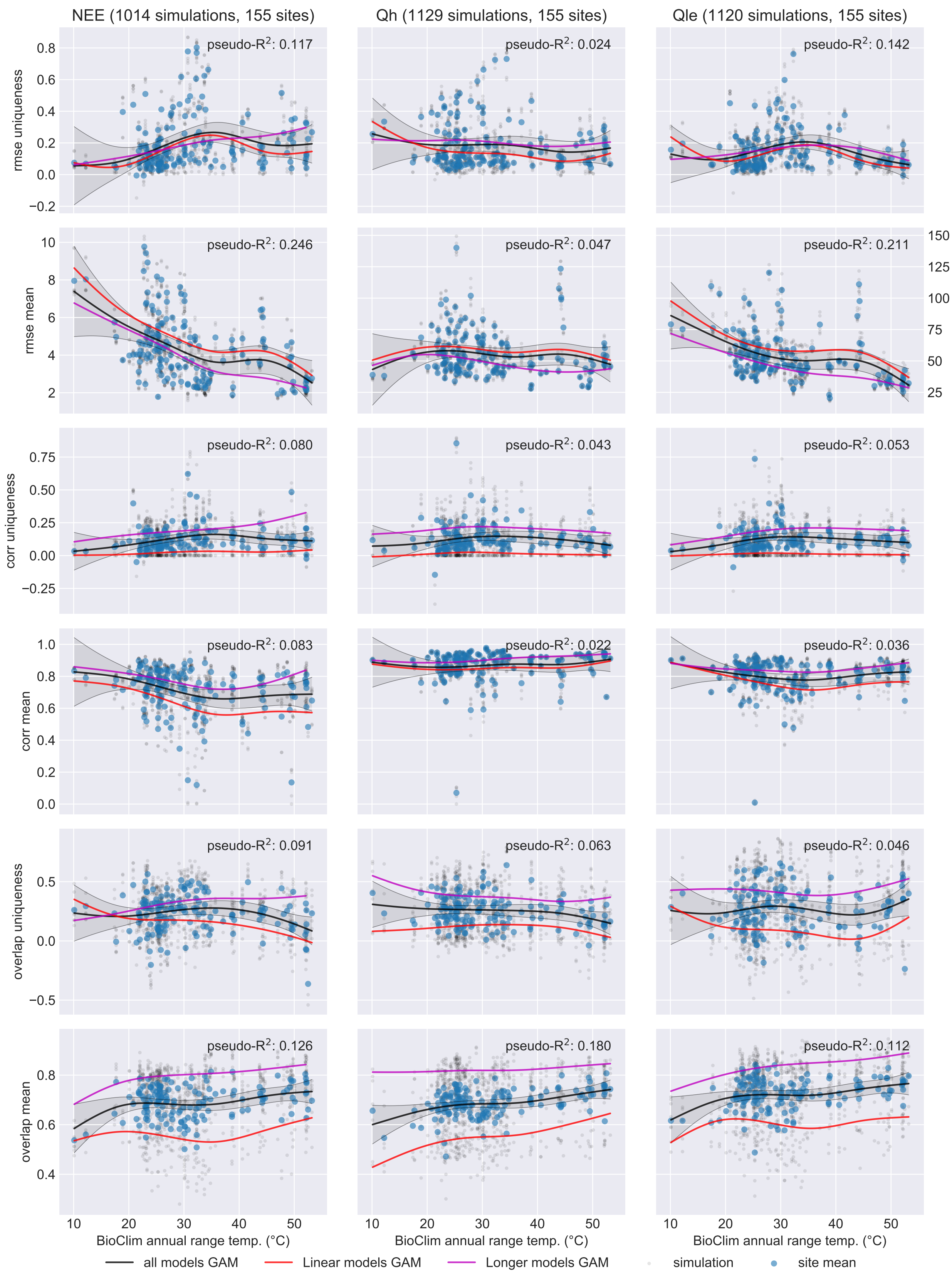


Figure 8: Predictability metrics for temperature annual range.

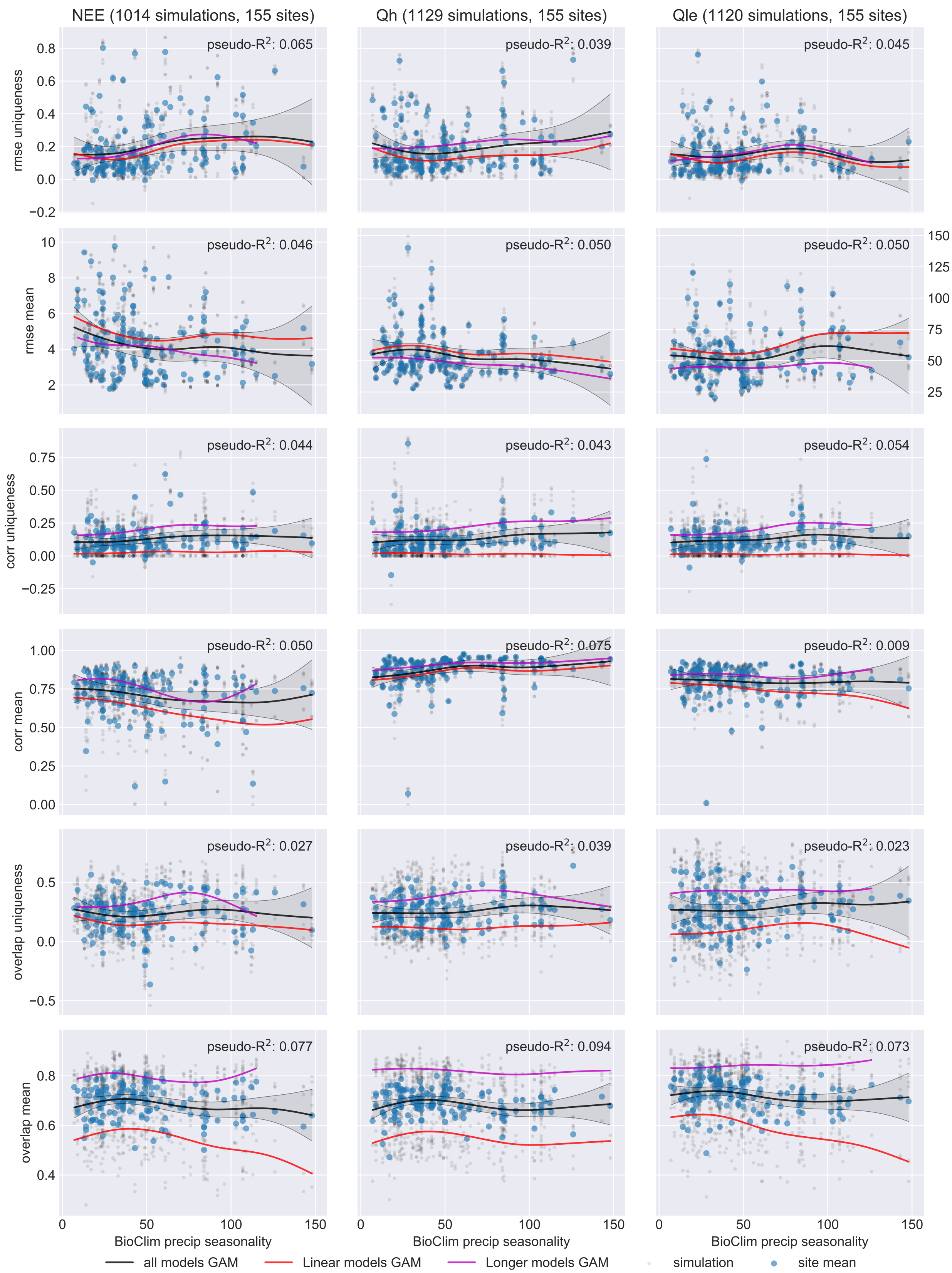


Figure 9: Predictability metrics for rainfall seasonality.

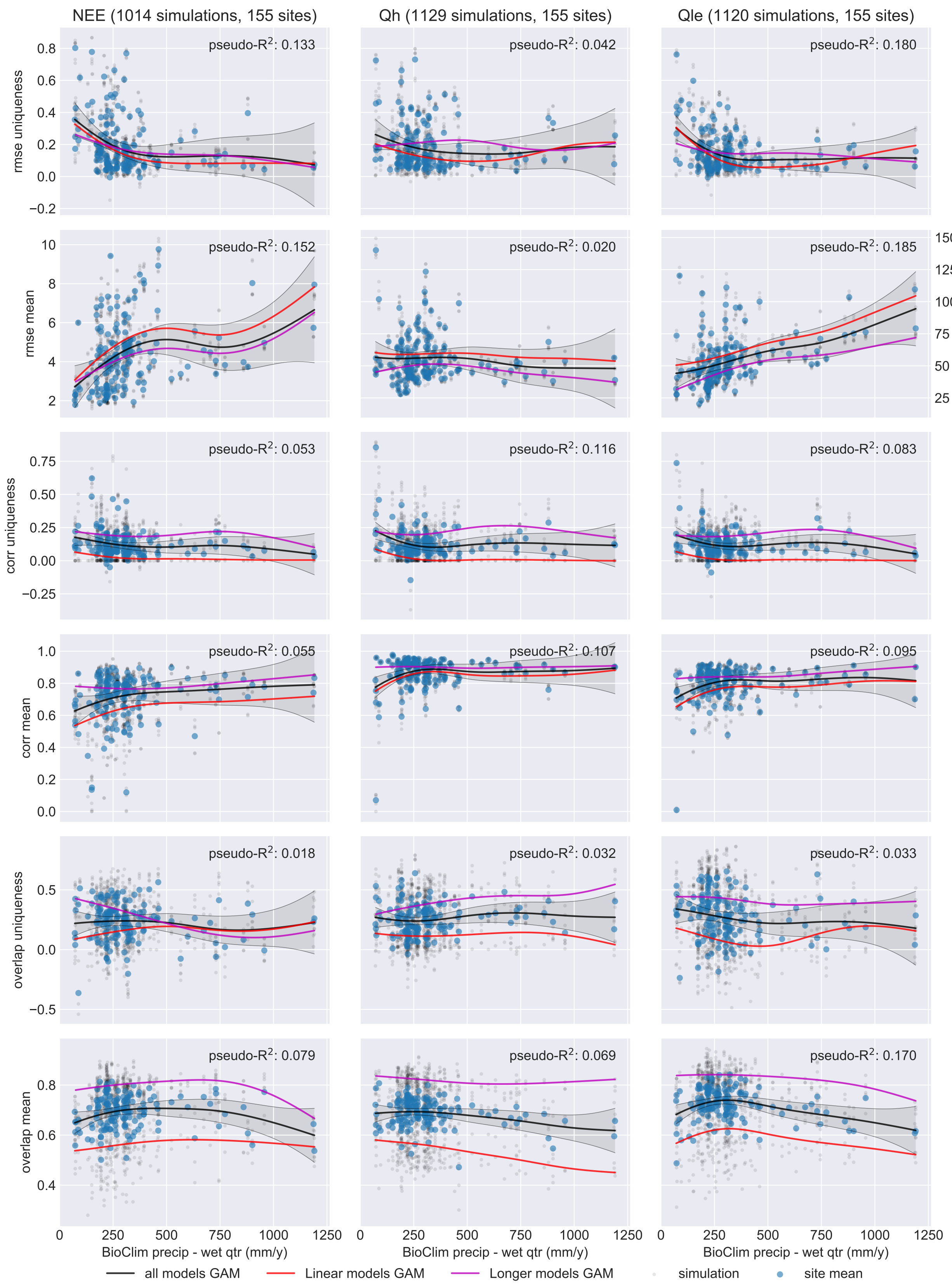


Figure 10: Predictability metrics for precipitation of the wettest quarter.

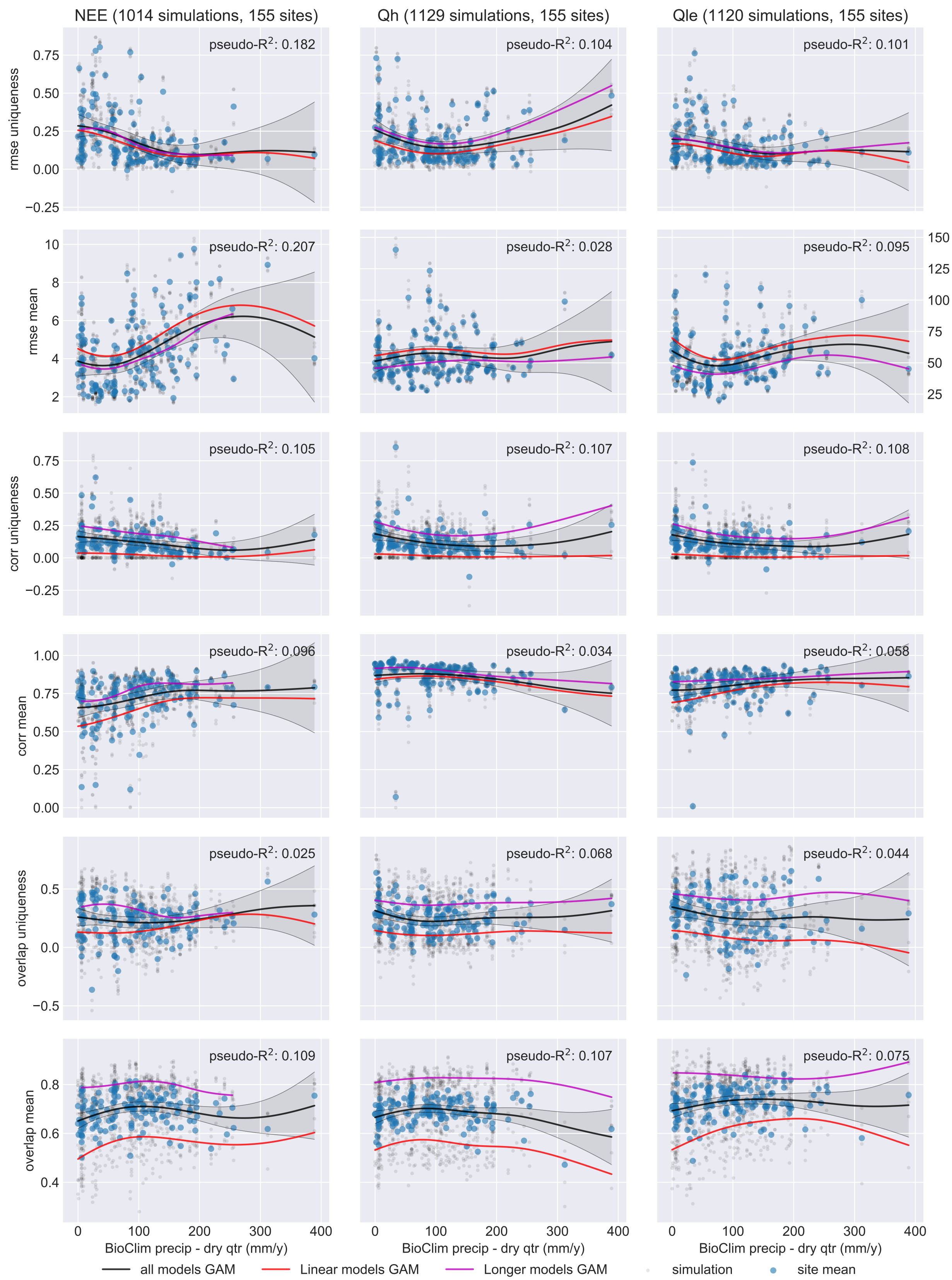


Figure 11: Predictability metrics for precipitation of the driest quarter.

Extended Vegetation type analysis

This figure shows the other predictability metrics for grouped vegetation type which were omitted from the paper.

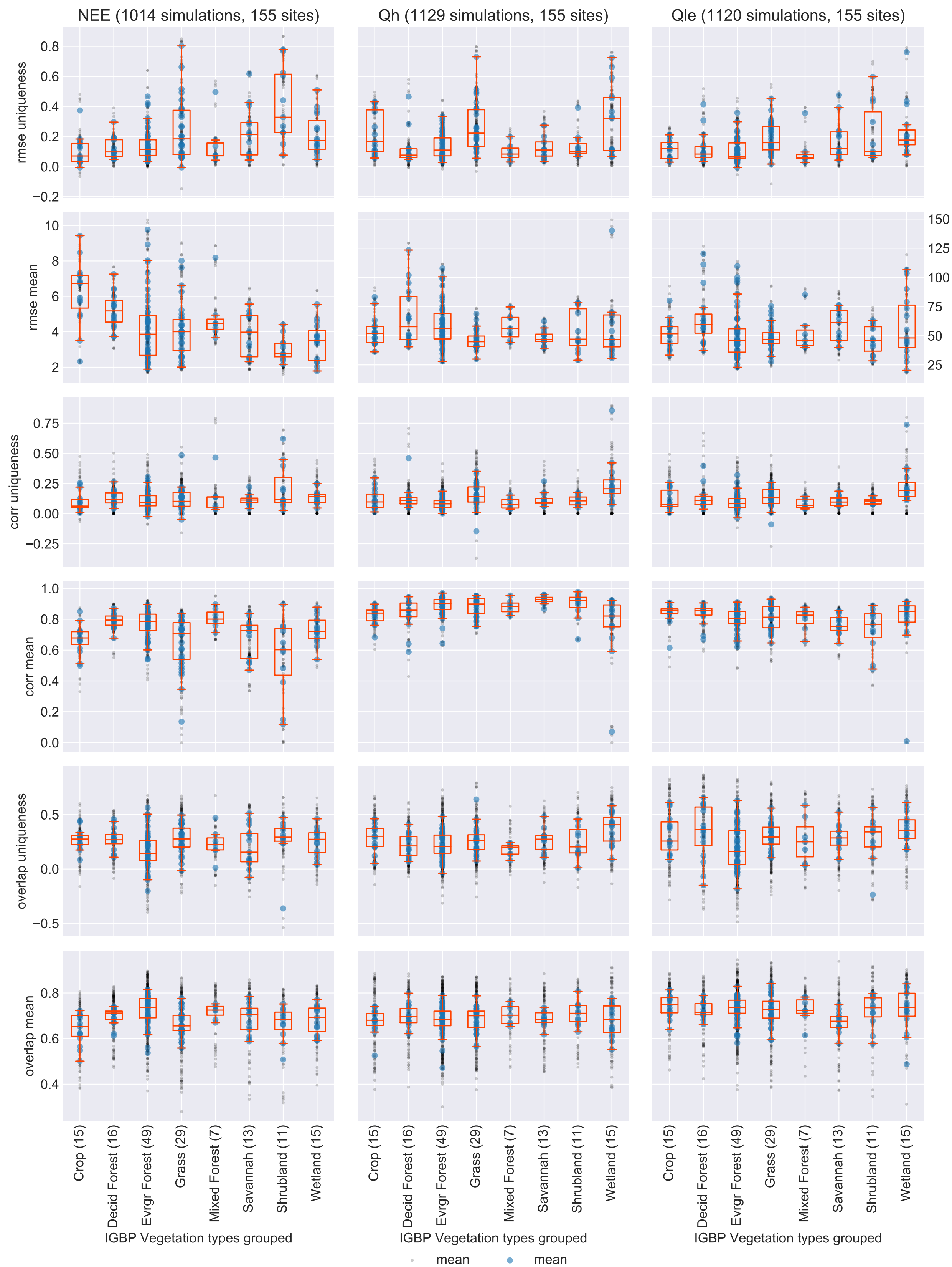


Figure 12: Predictability metrics for vegetation type (grouped, see Methods).

Geographic analysis

We are training the global models on all available sites, but FLUXNET sites are not evenly distributed over the land area of the globe. As such, we might expect that sites that have many other similar sites in the global dataset would have their behaviours more adequately captured by a globally trained model. To investigate whether more geographically unique sites were less predictable, we mapped the sites by uniqueness, and also compared uniqueness by average distance to all other sites.

Results

This section includes maps of RMSE uniqueness mean for Qh and Qle, mapped as per Figure 11 in the paper, as well as the remoteness predictability metrics. Distribution of uniqueness appears to be different for Qh (more high-uniqueness sites), but over-all, both variables have a similar, but lest distinct pattern of uniqueness as seen in NEE in Figure 11.

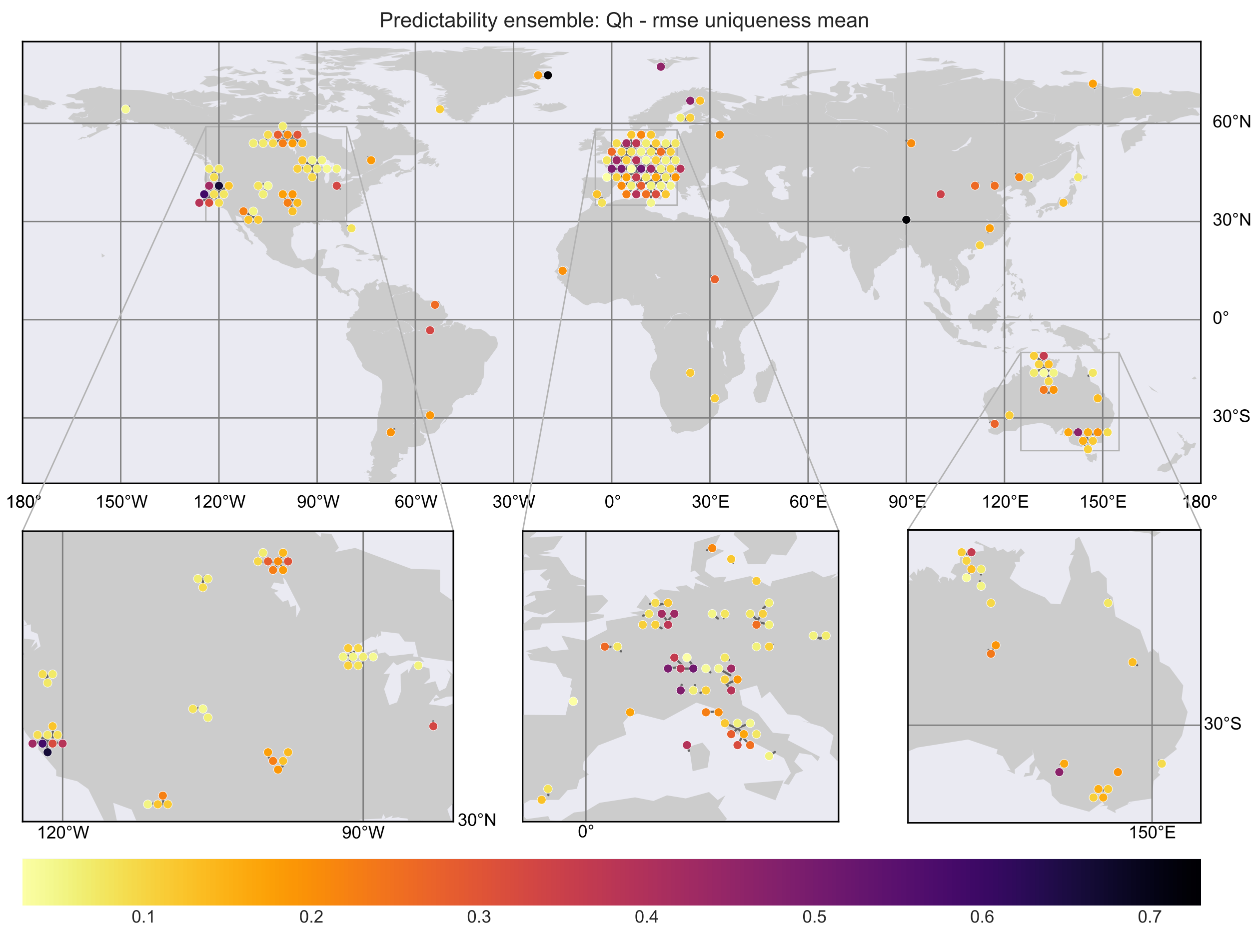


Figure 13: Map of Qh predictability - RMSE uniqueness, averaged across models, as per Figure 11 in the paper.

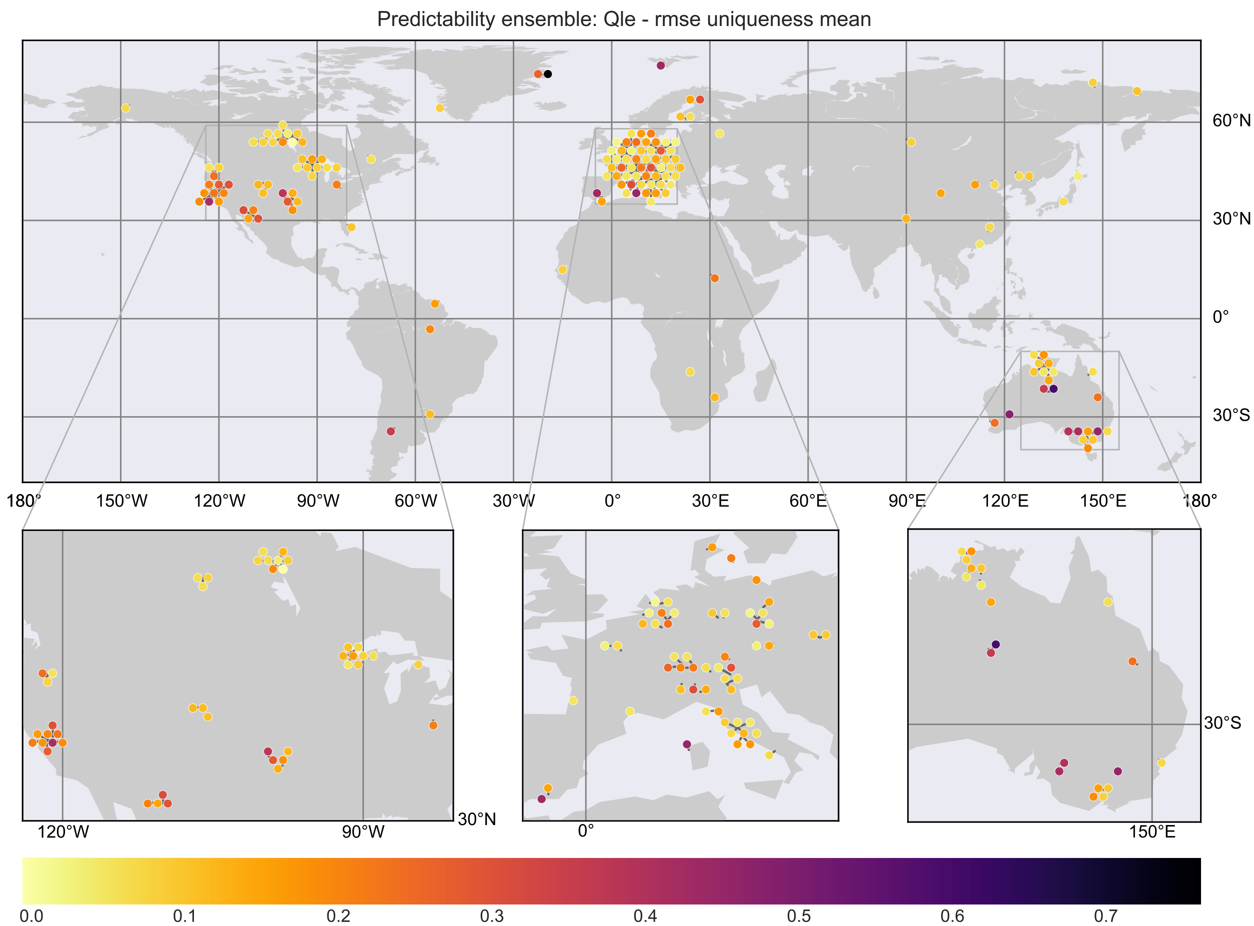


Figure 14: Map of Qle predictability - RMSE uniqueness, averaged across models, as per Figure 11 in the paper.

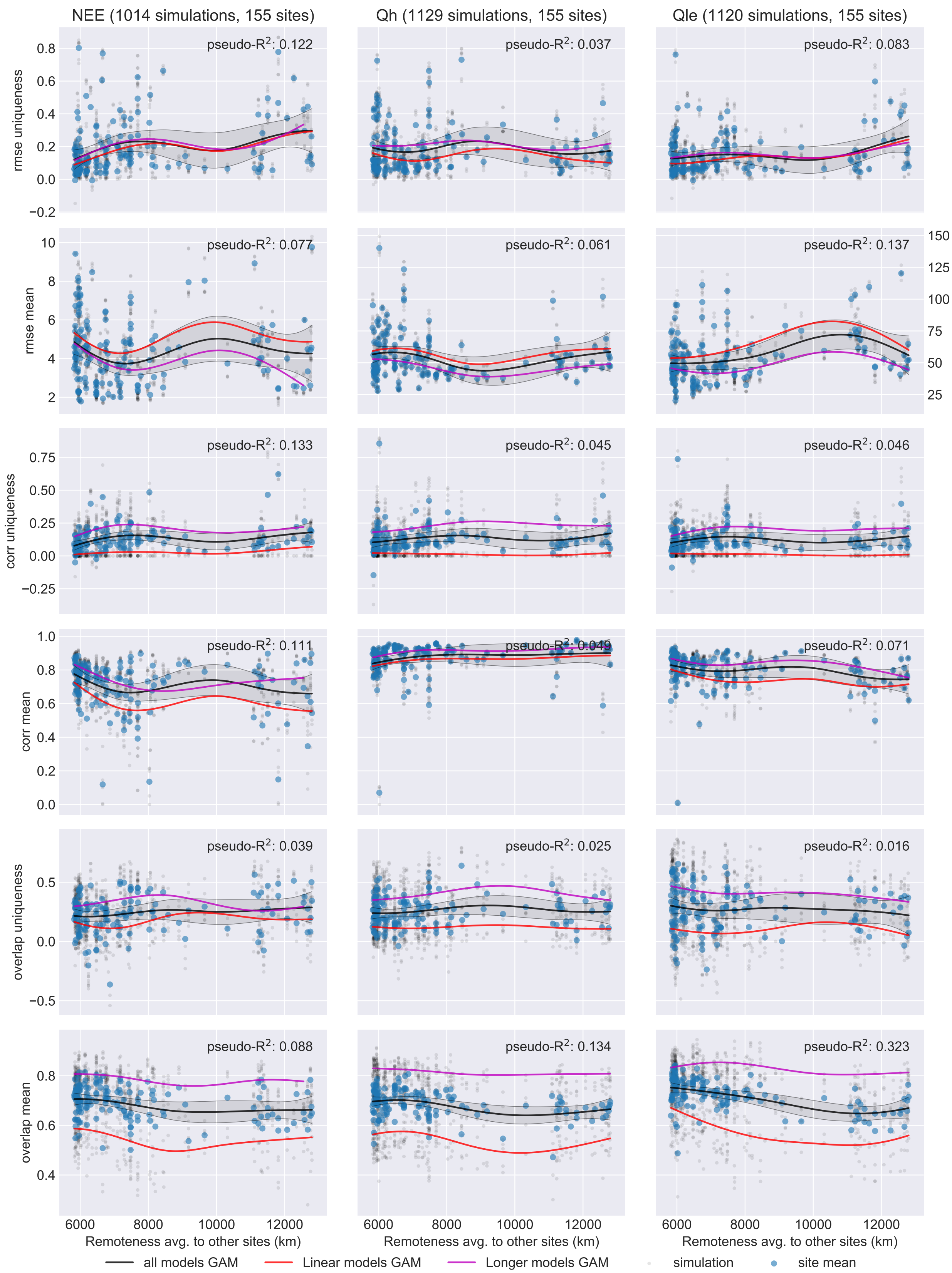
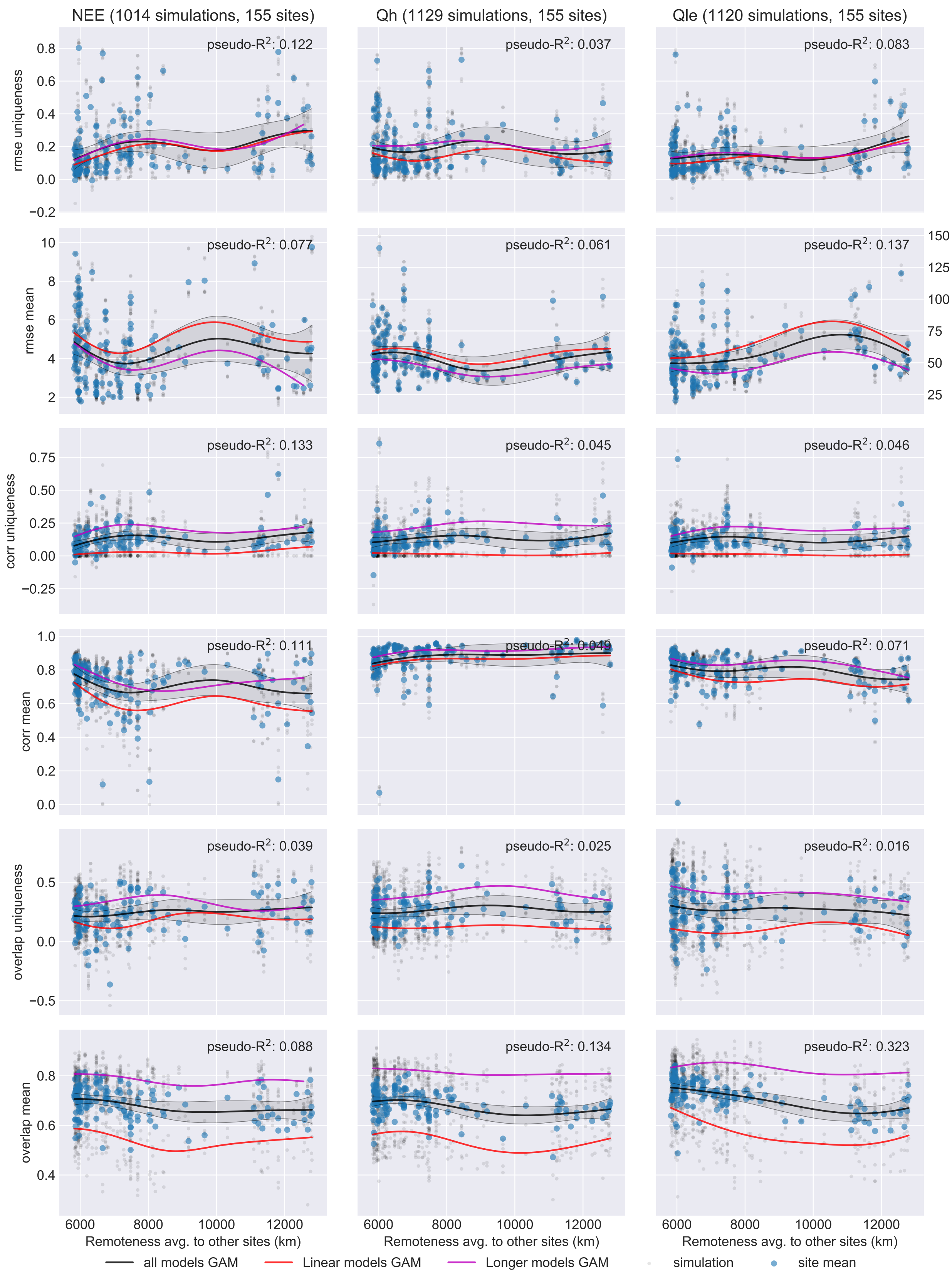


Figure 15: Predictability metrics by remoteness (average distance to all other sites)



Predictability metrics by average remoteness

Energy Gap Closure analysis

The energy closure problem in FLUXNET is investigated in Figure 16, where we show the actual gap (in W/m^2), and in Figure 17 where we show the absolute energy gap normalised by Rnet. In the first figure, there is no trend in any flux. In the second figure, there is appears to be a tend toward higher uncertainty in sites with large energy gaps relative to their total Rnet, however this trend is quite uncertain, due to the low number of sites involved.

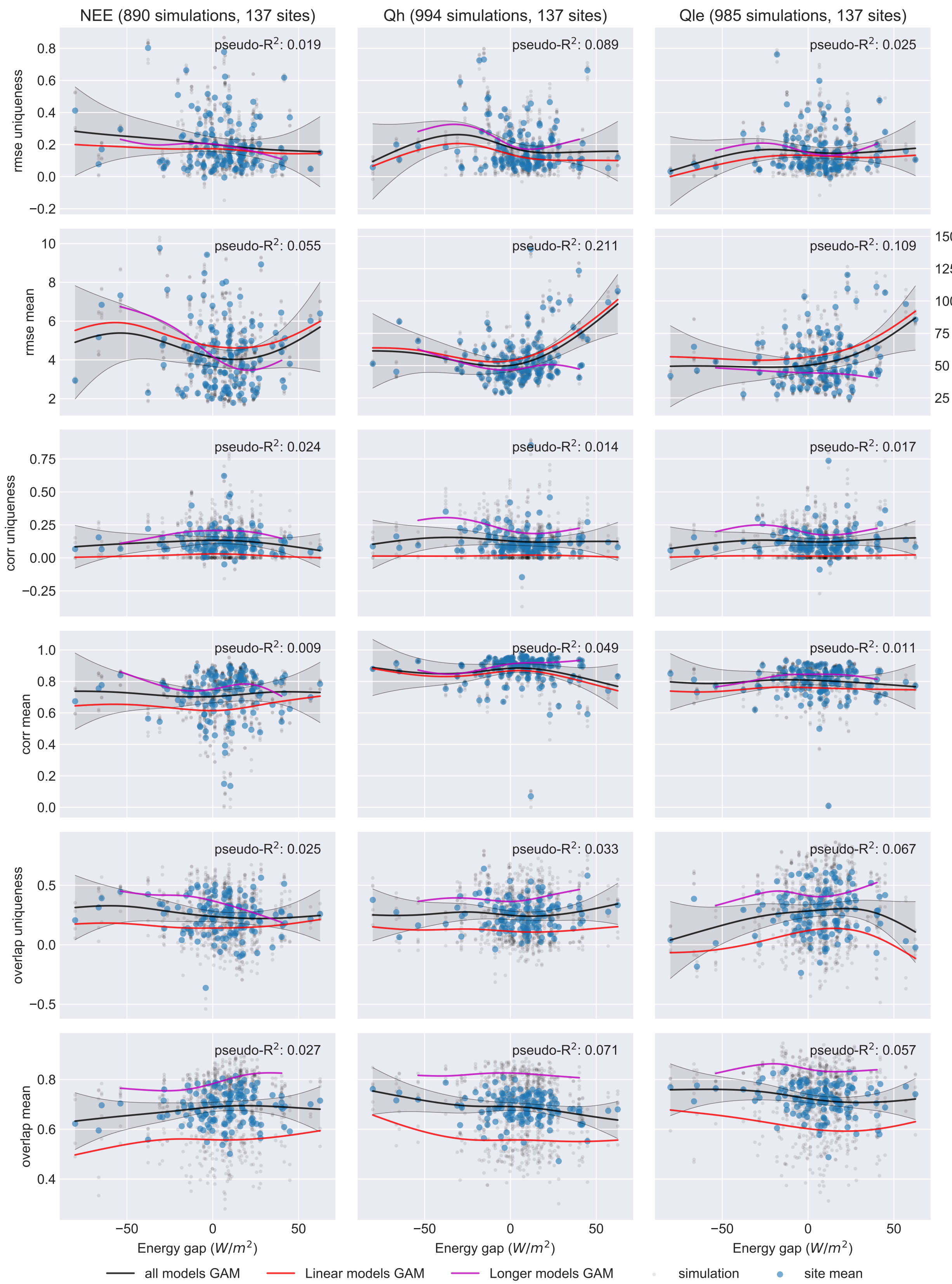


Figure 16: Predictability metrics for energy gap (W/m^2). Sites wth positive energy gaps have too much Rnet to relative to the over heat fluxes.

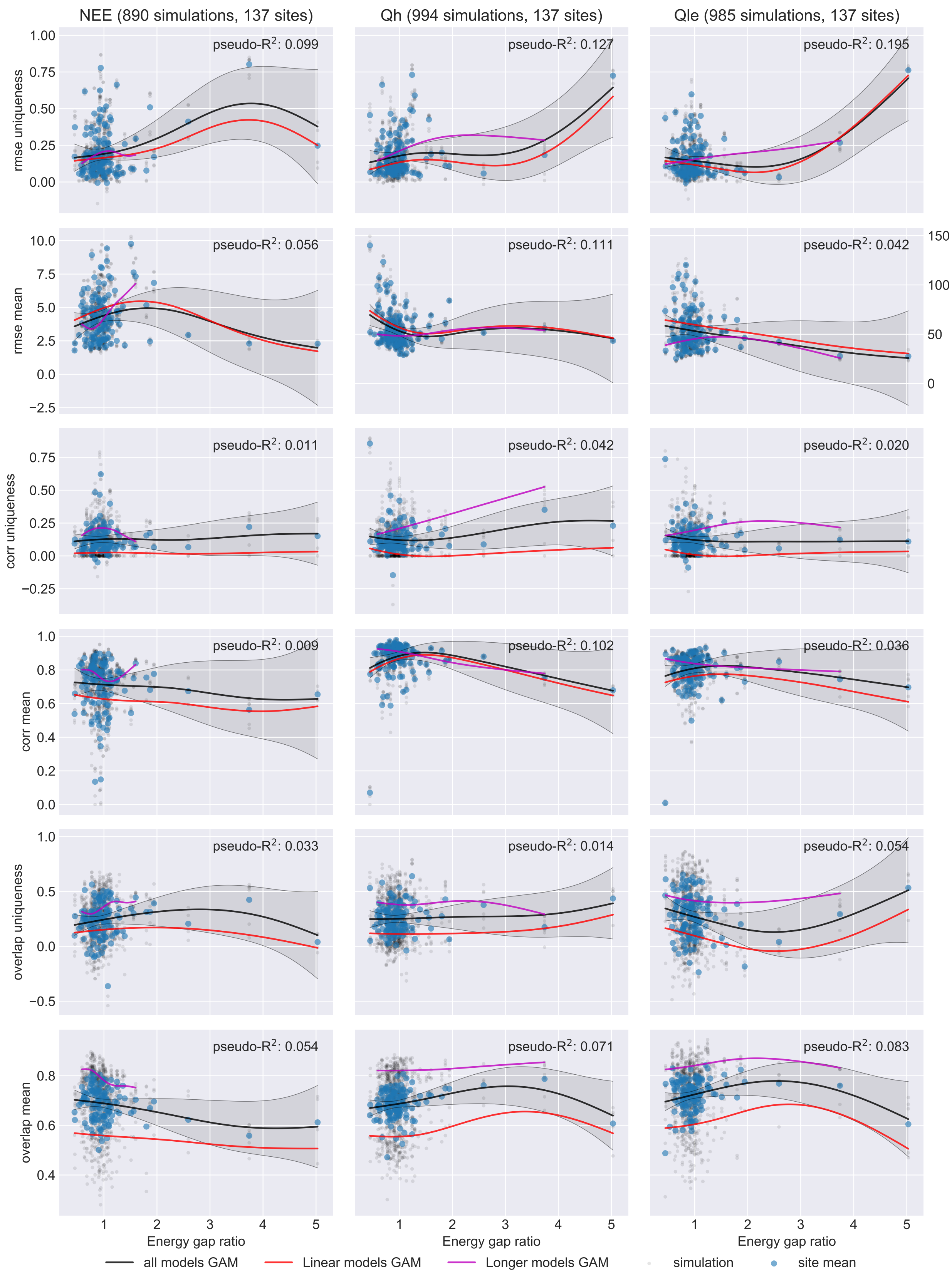
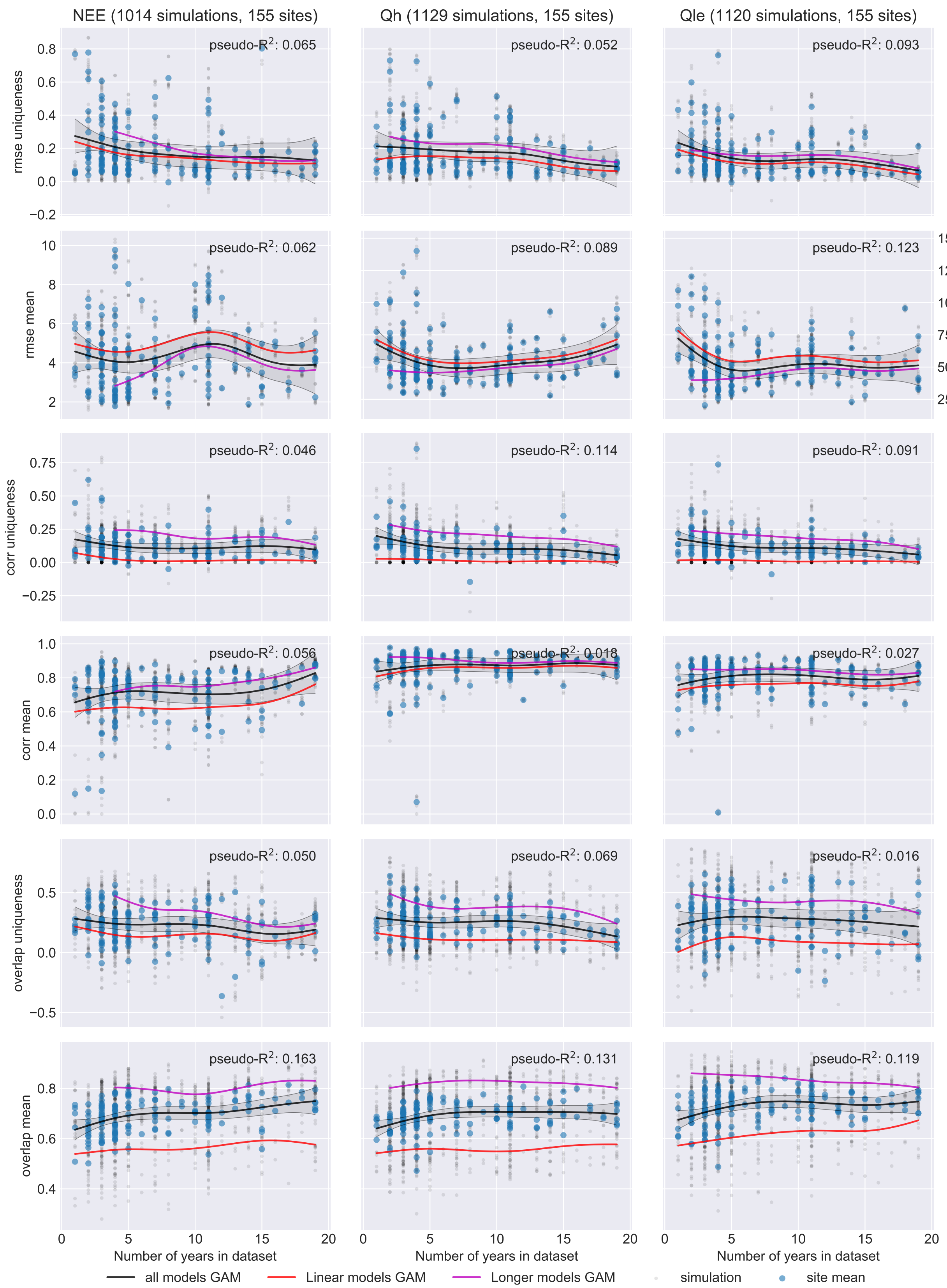


Figure 17: Predictability metrics for energy gap normalised by Rnet.

Extended dataset length analysis

The following plot shows the predictability metrics by data set length that were omitted from Figure 13.



Predictability metrics for number of years in dataset.

Fluxnet Citations

Sites, vegetation types, locations and studied periods of flux sites used in this analysis. All data originally from www.fluxdata.org, via https://github.com/trevorkeenan/FLUXNET_citations. Vegetation types: deciduous broadleaf forest (DBF); evergreen broadleaf forest (EBF); evergreen needleleaf forest (ENF); grassland (GRA); mixed deciduous and evergreen needleleaf forest (MF); savanna ecosystem (SAV); shrub ecosystem (SHR); wetland (WET).

Site code	Veg type	Latitude	Longitude	Period	References
AR-SLu	MF	-33.4648	-66.4598	2009-2011	(Ulke et al., 2015)
AR-Vir	ENF	-28.2395	-56.1886	2009-2012	(Posse et al., 2016)
AT-Neu	GRA	47.1167	11.3175	2002-2012	(Wohlfahrt et al., 2008)
AU-Ade	WSA	-13.0769	131.1178	2007-2009	(Beringer et al., 2011c)
AU-ASM	ENF	-22.2830	133.2490	2010-2013	(Cleverly et al., 2013)
AU-Cpr	SAV	-34.0021	140.5891	2010-2014	(Meyer et al., 2015)
AU-Cum	EBF	-33.6133	150.7225	2012-2014	(Beringer et al., 2016a)
AU-DaP	GRA	-14.0633	131.3181	2007-2013	(Beringer et al., 2011a)
AU-DaS	SAV	-14.1593	131.3881	2008-2014	(Hutley et al., 2011)
AU-Dry	SAV	-15.2588	132.3706	2008-2014	(Cernusak et al., 2011)
AU-Emr	GRA	-23.8587	148.4746	2011-2013	(Schroder et al., 2014)
AU-Fog	WET	-12.5452	131.3072	2006-2008	(Beringer et al., 2013)
AU-Gin	WSA	-31.3764	115.7138	2011-2014	(Beringer et al., 2016d)
AU-GWW	SAV	-30.1913	120.6541	2013-2014	(Prober et al., 2012)
AU-How	WSA	-12.4943	131.1523	2001-2014	(Cernusak, 2007)
AU-Lox	DBF	-34.4704	140.6551	2008-2009	(Stevens et al., 2011)
AU-RDF	WSA	-14.5636	132.4776	2011-2013	(Bristow et al., 2016)
AU-Rig	GRA	-36.6499	145.5759	2011-2014	(Beringer et al., 2016b)
AU-Rob	EBF	-17.1175	145.6301	2014-2014	(Beringer et al., 2016c)
AU-Stp	GRA	-17.1507	133.3502	2008-2014	(Beringer et al., 2011b)
AU-TTE	OSH	-22.2870	133.6400	2012-2013	(Cleverly et al., 2016)
AU-Wac	EBF	-37.4259	145.1878	2005-2008	(Kilinc et al., 2013)
AU-Whr	EBF	-36.6732	145.0294	2011-2014	(McHugh et al., 2017)
AU-Wom	EBF	-37.4222	144.0944	2010-2012	(Hinko-Najera et al., 2017)
AU-Ync	GRA	-34.9893	146.2907	2012-2014	(Yee et al., 2015)
BE-Bra	MF	51.3092	4.5206	1996-2014	(Carrara et al., 2004)
BE-Lon	CRO	50.5516	4.7461	2004-2014	(Moureaux et al., 2006)
BE-Vie	MF	50.3051	5.9981	1996-2014	(Aubinet et al., 2001)
BR-Sa3	EBF	-3.0180	-54.9714	2000-2004	(Wick et al., 2005)
CA-Man	ENF	55.8796	-98.4808	1994-2008	(Dunn et al., 2007)
CA-NS1	ENF	55.8792	-98.4839	2001-2005	(Goulden et al., 2006a)
CA-NS2	ENF	55.9058	-98.5247	2001-2005	(Goulden et al., 2006b)
CA-NS3	ENF	55.9117	-98.3822	2001-2005	(Goulden et al., 2006c)
CA-NS4	ENF	55.9144	-98.3806	2002-2005	(Goulden et al., 2006d)
CA-NS5	ENF	55.8631	-98.4850	2001-2005	(Goulden et al., 2006e)
CA-NS6	OSH	55.9167	-98.9644	2001-2005	(Goulden et al., 2006f)
CA-NS7	OSH	56.6358	-99.9483	2002-2005	(Goulden et al., 2006g)
CA-Qfo	ENF	49.6925	-74.3421	2003-2010	(Bergeron et al., 2007)
CA-SF1	ENF	54.4850	-105.8176	2003-2006	(Mkhabela et al., 2009a)
CA-SF2	ENF	54.2539	-105.8775	2001-2005	(Mkhabela et al., 2009b)
CA-SF3	OSH	54.0916	-106.0053	2001-2006	(Mkhabela et al., 2009c)
CH-Cha	GRA	47.2102	8.4104	2005-2014	(Merbold et al., 2014)
CH-Dav	ENF	46.8153	9.8559	1997-2014	(Zielis et al., 2014)

Site code	Veg type	Latitude	Longitude	Period	References
CH-Fru	GRA	47.1158	8.5378	2005-2014	(Imer et al., 2013)
CH-Lae	MF	47.4781	8.3650	2004-2014	(Etzold et al., 2011)
CH-Oe1	GRA	47.2858	7.7319	2002-2008	(Ammann et al., 2009)
CH-Oe2	CRO	47.2863	7.7343	2004-2014	(Dietiker et al., 2010)
CN-Cha	MF	42.4025	128.0958	2003-2005	(Guan et al., 2006)
CN-Cng	GRA	44.5934	123.5092	2007-2010	(**???**)
CN-Dan	GRA	30.4978	91.0664	2004-2005	(Shi et al., 2006)
CN-Din	EBF	23.1733	112.5361	2003-2005	(Yan et al., 2013)
CN-Du2	GRA	42.0467	116.2836	2006-2008	(Chen et al., 2009)
CN-Ha2	WET	37.6086	101.3269	2003-2005	(**???**)
CN-HaM	GRA	37.3700	101.1800	2002-2004	(Kato et al., 2006)
CN-Qia	ENF	26.7414	115.0581	2003-2005	(Wen et al., 2010)
CN-Sw2	GRA	41.7902	111.8971	2010-2012	(Shao et al., 2017)
CZ-BK1	ENF	49.5021	18.5369	2004-2008	(Acosta et al., 2013)
CZ-BK2	GRA	49.4944	18.5429	2004-2006	(**???**)
CZ-wet	WET	49.0247	14.7704	2006-2014	(Dušek et al., 2012)
DE-Akm	WET	53.8662	13.6834	2009-2014	(**???**)
DE-Geb	CRO	51.1001	10.9143	2001-2014	(Anthoni et al., 2004)
DE-Gri	GRA	50.9500	13.5126	2004-2014	(Prescher et al., 2010a)
DE-Hai	DBF	51.0792	10.4530	2000-2012	(Knohl et al., 2003)
DE-Kli	CRO	50.8931	13.5224	2004-2014	(Prescher et al., 2010b)
DE-Lkb	ENF	49.0996	13.3047	2009-2013	(Lindauer et al., 2014)
DE-Obe	ENF	50.7867	13.7213	2008-2014	(**???**)
DE-RuR	GRA	50.6219	6.3041	2011-2014	(Post et al., 2015)
DE-RuS	CRO	50.8659	6.4472	2011-2014	(Mauder et al., 2013)
DE-Seh	CRO	50.8706	6.4497	2007-2010	(Schmidt et al., 2012)
DE-SfN	WET	47.8064	11.3275	2012-2014	(Hommeltenberg et al., 2014)
DE-Spw	WET	51.8923	14.0337	2010-2014	(**???**)
DE-Tha	ENF	50.9624	13.5652	1996-2014	(Grünwald and Bernhofer, 2007)
DK-Fou	CRO	56.4842	9.5872	2005-2005	(**???**)
DK-NuF	WET	64.1308	-51.3861	2008-2014	(Westergaard-Nielsen et al., 2013)
DK-Sor	DBF	55.4859	11.6446	1996-2014	(Pilegaard et al., 2011)
DK-ZaF	WET	74.4814	-20.5545	2008-2011	(Stiegler et al., 2016)
DK-ZaH	GRA	74.4732	-20.5503	2000-2014	(Lund et al., 2012)
ES-LgS	OSH	37.0979	-2.9658	2007-2009	(Reverter et al., 2010)
ES-Ln2	OSH	36.9695	-3.4758	2009-2009	(Serrano-Ortiz et al., 2011)
FI-Hyy	ENF	61.8474	24.2948	1996-2014	(Suni et al., 2003)
FI-Jok	CRO	60.8986	23.5135	2000-2003	(Lohila, 2004)
FI-Lom	WET	67.9972	24.2092	2007-2009	(Aurela et al., 2015)
FI-Sod	ENF	67.3619	26.6378	2001-2014	(Thum et al., 2007)
FR-Fon	DBF	48.4764	2.7801	2005-2014	(Delpierre et al., 2015)
FR-Gri	CRO	48.8442	1.9519	2004-2013	(Loubet et al., 2011)
FR-LBr	ENF	44.7171	-0.7693	1996-2008	(Berbigier et al., 2001)
FR-Pue	EBF	43.7414	3.5958	2000-2014	(Rambal et al., 2004)
GF-Guy	EBF	5.2788	-52.9249	2004-2014	(Bonal et al., 2008)
IT-BCi	CRO	40.5238	14.9574	2004-2014	(Vitale et al., 2015)
IT-CA1	DBF	42.3804	12.0266	2011-2014	(Sabbatini et al., 2016a)
IT-CA2	CRO	42.3772	12.0260	2011-2014	(Sabbatini et al., 2016b)
IT-CA3	DBF	42.3800	12.0222	2011-2014	(Sabbatini et al., 2016c)
IT-Col	DBF	41.8494	13.5881	1996-2014	(Valentini et al., 1996)
IT-Cp2	EBF	41.7043	12.3573	2012-2014	(Fares et al., 2014)
IT-Cpz	EBF	41.7052	12.3761	1997-2009	(Garbulsky et al., 2008)

Site code	Veg type	Latitude	Longitude	Period	References
IT-Isp	DBF	45.8126	8.6336	2013-2014	(Ferréa et al., 2012)
IT-La2	ENF	45.9542	11.2853	2000-2002	(Marcolla et al., 2003a)
IT-Lav	ENF	45.9562	11.2813	2003-2014	(Marcolla et al., 2003b)
IT-MBo	GRA	46.0147	11.0458	2003-2013	(Marcolla et al., 2011)
IT-Noe	CSH	40.6061	8.1515	2004-2014	(Papale et al., 2014)
IT-PT1	DBF	45.2009	9.0610	2002-2004	(Migliavacca et al., 2009)
IT-Ren	ENF	46.5869	11.4337	1998-2013	(Montagnani et al., 2009)
IT-Ro1	DBF	42.4081	11.9300	2000-2008	(Rey et al., 2002)
IT-Ro2	DBF	42.3903	11.9209	2002-2012	(Tedeschi et al., 2006)
IT-SR2	ENF	43.7320	10.2910	2013-2014	(Hoshika et al., 2017)
IT-SRo	ENF	43.7279	10.2844	1999-2012	(Chiesi et al., 2005)
IT-Tor	GRA	45.8444	7.5781	2008-2014	(Galvagno et al., 2013)
JP-MBF	DBF	44.3869	142.3186	2003-2005	(Matsumoto et al., 2008a)
JP-SMF	MF	35.2617	137.0788	2002-2006	(Matsumoto et al., 2008b)
NL-Hor	GRA	52.2404	5.0713	2004-2011	(Jacobs et al., 2007)
NL-Loo	ENF	52.1666	5.7436	1996-2013	(Moors, 2012)
NO-Adv	WET	78.1860	15.9230	2011-2014	(**???**)
RU-Che	WET	68.6130	161.3414	2002-2005	(Merbold et al., 2009a)
RU-Cok	OSH	70.8291	147.4943	2003-2014	(Molen et al., 2007)
RU-Fyo	ENF	56.4615	32.9221	1998-2014	(Kurbatova et al., 2008)
RU-Ha1	GRA	54.7252	90.0022	2002-2004	(Marchesini et al., 2007)
SD-Dem	SAV	13.2829	30.4783	2005-2009	(Ardo et al., 2008)
SN-Dhr	SAV	15.4028	-15.4322	2010-2013	(Tagesson et al., 2014)
US-AR1	GRA	36.4267	-99.4200	2009-2012	(Raz-Yaseef et al., 2015b)
US-AR2	GRA	36.6358	-99.5975	2009-2012	(Raz-Yaseef et al., 2015c)
US-ARb	GRA	35.5497	-98.0402	2005-2006	(Raz-Yaseef et al., 2015a)
US-ARc	GRA	35.5465	-98.0400	2005-2006	(Raz-Yaseef et al., 2015d)
US-ARM	CRO	36.6058	-97.4888	2003-2012	(Fischer et al., 2007)
US-Blo	ENF	38.8953	-120.6328	1997-2007	(Goldstein et al., 2000)
US-GBT	ENF	41.3658	-106.2397	1999-2006	(Zeller and Nikolov, 2000)
US-GLE	ENF	41.3665	-106.2399	2004-2014	(Frank et al., 2014)
US-KS2	CSH	28.6086	-80.6715	2003-2006	(Powell et al., 2006)
US-Los	WET	46.0827	-89.9792	2000-2014	(Sulman et al., 2009)
US-Me1	ENF	44.5794	-121.5000	2004-2005	(Irvine et al., 2007)
US-Me2	ENF	44.4523	-121.5574	2002-2014	(Irvine et al., 2008)
US-Me6	ENF	44.3233	-121.6078	2010-2014	(Ruehr et al., 2012)
US-Myb	WET	38.0498	-121.7651	2010-2014	(Matthes et al., 2014)
US-NR1	ENF	40.0329	-105.5464	1998-2014	(Monson et al., 2002)
US-ORv	WET	40.0201	-83.0183	2011-2011	(Morin et al., 2014)
US-Prr	ENF	65.1237	-147.4876	2010-2013	(Nakai et al., 2013)
US-SRG	GRA	31.7894	-110.8277	2008-2014	(Scott et al., 2015a)
US-SRM	WSA	31.8214	-110.8661	2004-2014	(Scott et al., 2009)
US-Syv	MF	46.2420	-89.3477	2001-2014	(Desai et al., 2005)
US-Ton	WSA	38.4316	-120.9660	2001-2014	(Baldocchi et al., 2010)
US-Tw1	WET	38.1074	-121.6469	2012-2014	(Oikawa et al., 2017)
US-Tw2	CRO	38.1047	-121.6433	2012-2013	(Knox et al., 2016)
US-Tw3	CRO	38.1159	-121.6467	2013-2014	(Baldocchi et al., 2015)
US-Tw4	WET	38.1030	-121.6414	2013-2014	(Baldocchi, 2016)
US-Twt	CRO	38.1087	-121.6530	2009-2014	(Hatala et al., 2012)
US-UMd	DBF	45.5625	-84.6975	2007-2014	(Gough et al., 2013)
US-Var	GRA	38.4133	-120.9507	2000-2014	(Ma et al., 2007)
US-WCr	DBF	45.8059	-90.0799	1999-2014	(Cook et al., 2004)

Site code	Veg type	Latitude	Longitude	Period	References
US-Whs	OSH	31.7438	-110.0522	2007-2014	(Scott et al., 2015b)
US-Wi0	ENF	46.6188	-91.0814	2002-2002	(Noormets et al., 2007a)
US-Wi3	DBF	46.6347	-91.0987	2002-2004	(Noormets et al., 2007b)
US-Wi4	ENF	46.7393	-91.1663	2002-2005	(Noormets et al., 2007c)
US-Wi6	OSH	46.6249	-91.2982	2002-2003	(Noormets et al., 2007d)
US-Wi9	ENF	46.6188	-91.0814	2004-2005	(Noormets et al., 2007e)
US-Wkg	GRA	31.7365	-109.9419	2004-2014	(Scott et al., 2010)
ZA-Kru	SAV	-25.0197	31.4969	2000-2010	(Archibald et al., 2009)
ZM-Mon	DBF	-15.4378	23.2528	2000-2009	(Merbold et al., 2009b)

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