

1 **Supplementary information**

2 **Text S1**

3 **Estimation of crop height and rooting depth**

4 Crop height is simulated as a simple function of crop development. Plant height increases with
5 the heat-unit factor and approaches a crop-specific maximum height at later growth stages:

$$6 \qquad \qquad \qquad CH_t = HCM \times \sqrt{HUF_t}$$

7 where CH_t is crop height in m at day t and HCM is the maximum crop height in m (Table 1).

8 Rooting depth is simulated as a function of heat units and potential root zone depth:

$$9 \qquad \qquad \qquad RD_t = \min(2.5 \times RDM \times HUI_t, RDM, RZ)$$

10 where RD_t is the root depth in m at day t, RDM is the maximum rooting depth of the crop in
11 m (Table 1), and RZ is the total soil profile depth in m.

12 **Biomass allocation**

13 The simulated biomass is then partitioned between roots and aboveground biomass according
14 to crop development. The fraction allocated to roots decreases with crop development, so
15 relatively more biomass is invested in roots during the early growth stage and more biomass is
16 allocated to aboveground organs later in the season (Hacker and Jones, 1988). Root biomass is
17 calculated as

$$18 \qquad \qquad \qquad RW_t = TM_t \times (RTF_1 \times (1 - HUI_t) + RTF_2 \times HUI_t)$$

19 where RW_t is total root biomass in t ha⁻¹ at day t, TM_t is total biomass in t ha⁻¹ at day t, and
20 RTF_1 and RTF_2 are crop-specific parameters (Table 1). The daily change in root biomass is
21 further distributed over the root zone according to water uptake by each soil layer. Aboveground

biomass AGB is then obtained as the difference between total biomass and root biomass.

Actual harvest index estimation

The harvest index is adjusted by the heat unit index because the harvest index increases with crop development and approaches its potential value as the crop reaches physiological maturity.

It is calculated as follows:

$$AJHI = HIO * (100 * HUI) / ((100 * HUI) + \exp(11.11 - 0.1 * (100 * HUI)))$$

where *AJHI* is the potential harvest index under non-water-stressed conditions, and *HIO* is the potential harvest index at maturity (Table 1).

As described by Williams et al. (1984), actual yield can be affected by water-stress-induced changes in the harvest index. For many grain crops, water stress around anthesis has a particularly strong influence on yield components and therefore on the final harvest index (Doorenbos and Kassam, 1979). The actual harvest index is calculated as follows:

$$HIF = F \times (AJHI - HIL) + HIL$$

$$F = CWF / (CWF + \exp(5.563 - 0.0316 * CWF))$$

$$CWF = 100 * \frac{SWA}{SWP}$$

where *HIF* is the actual harvest index, *HIL* is the minimum harvest index (Table 1), and *CWF* is the crop water factor, calculated as the percentage ratio of total actual crop water use (*SWA*) to potential crop water demand (*SWP*) during the growth stage that has the greatest influence on harvest-index formation.

Estimation of potential crop-specific evapotranspiration and transpiration

Potential evapotranspiration (PET) is estimated using the Penman–Monteith method (Monteith, 1965):

$$44 \quad PET_t = \frac{RN_t \times DLT_t + 86.66 \times RHO_t \times \frac{VPD_t}{RV_t}}{XL_t \times (DLT_t + GMA_t)}$$

45 where PET_t is the potential evapotranspiration in mm d⁻¹ at day t, RN_t is the net radiation in
 46 MJ m⁻² d⁻¹ at day t, DLT_t is the slope of the saturation vapour pressure curve in kPa °C⁻¹,
 47 RHO_t is the air density in kg m⁻³ at day t, VPD_t is the vapour pressure deficit in kPa at day t,
 48 RV_t is the aerodynamic resistance to heat and vapour transfer at day t, XL_t is the latent heat
 49 of vaporization in MJ kg⁻¹ at day t, and GMA_t is the psychrometric constant at day t.
 50 Potential plant transpiration is calculated as follows:

$$51 \quad PT_t = \frac{RN_t \times DLT_t + 86.66 \times RHO_t \times \frac{VPD_t}{RV_t}}{XL_t \times \left(DLT_t + GMA_t * \left(1 + \frac{RC_t}{RV_t} \right) \right)}$$

$$52 \quad RC_t = \frac{PM_{cano}}{LAI_t \times GSM \times FVPD \times \exp(0.00155 \times (330 - CO_2))}$$

53 where PT_t is the potential plant transpiration in mm d⁻¹ at day t, RC_t is the canopy resistance
 54 to vapour transfer in s m⁻¹ at day t, PM_{cano} is a parameter to adjust crop canopy resistance ,
 55 set to 1 in this study, LAI_t is leaf area index in m² m⁻² at day t, GSM is crop-specific maximum
 56 stomatal conductance, $FVPD$ is the limiting factor of VPD on stomatal conductance, and CO_2
 57 is atmospheric CO₂ concentration in ppm and was fixed at 330 ppm in this study.

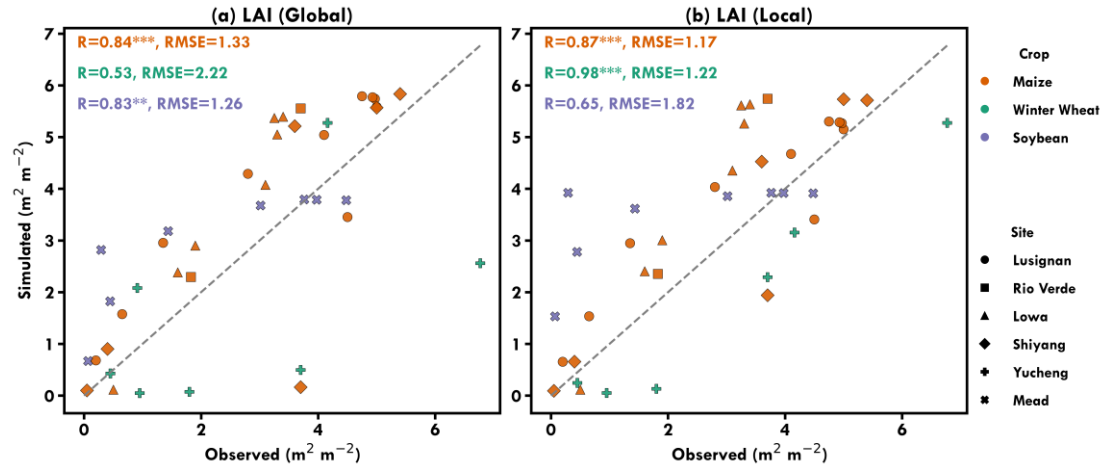


Figure S1. Comparison of simulated and observed LAI across the evaluation sites. Scatter plots compare simulated and observed LAI across the selected sites using (a) the global and (b) the local sowing date. Colors indicate crop types, and symbols indicate sites. The dashed line represents the 1:1 line. Summary statistics are shown separately for maize, winter wheat, and soybean. The symbols *, **, and *** indicate p values < 0.05 , 0.01 , and 0.001 . Units are $\text{m}^2 \text{m}^{-2}$.

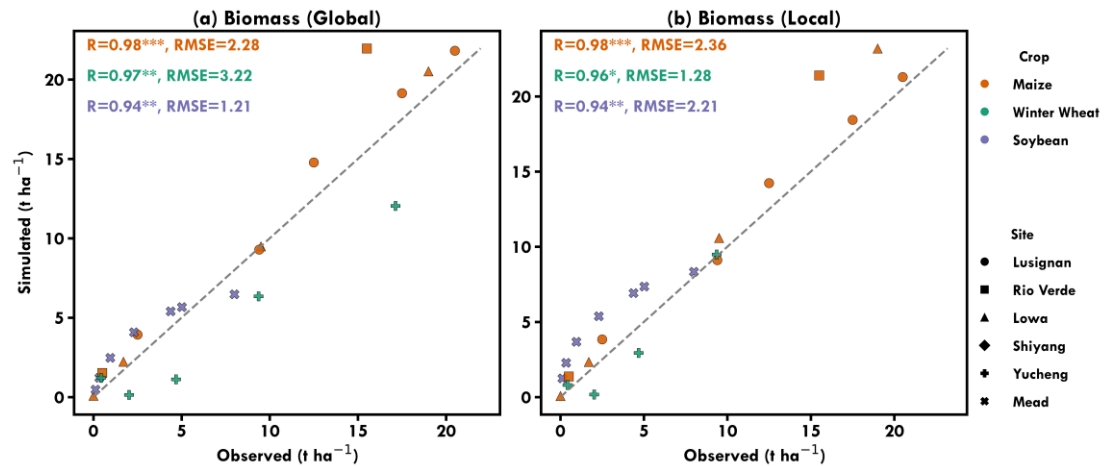
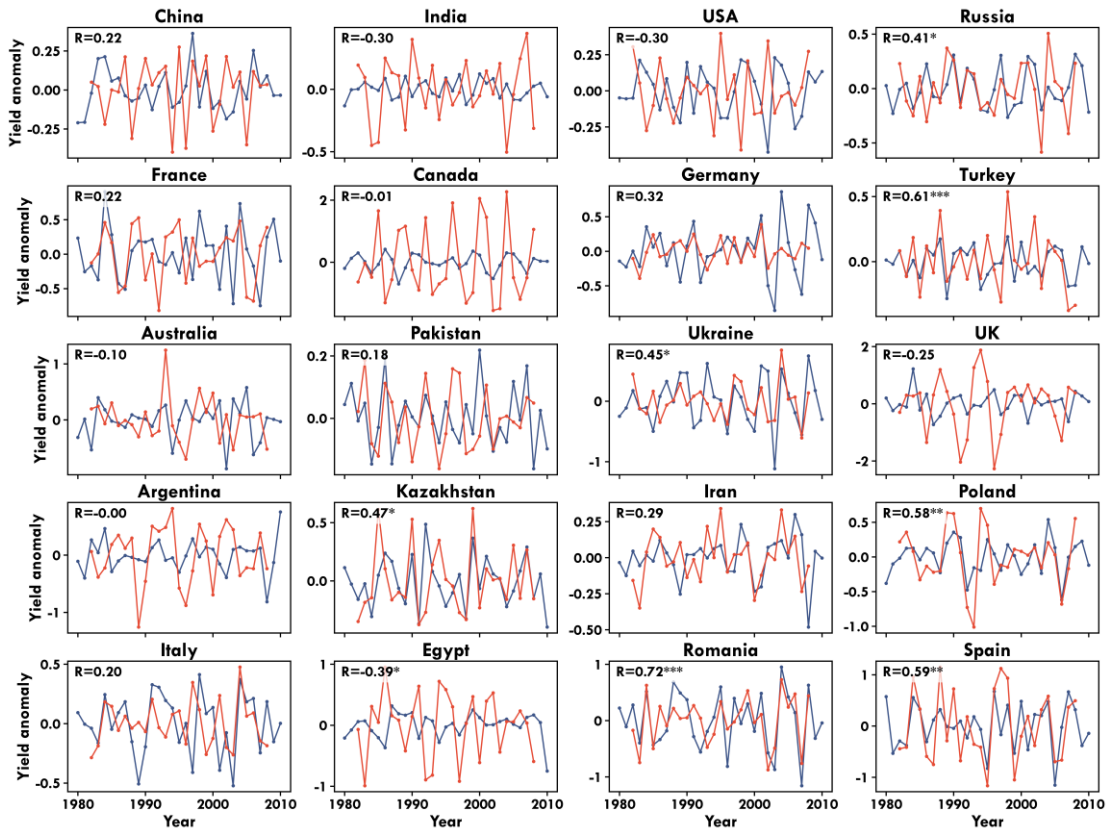


Figure S2. Comparison of simulated and observed biomass across the evaluation sites. Scatter plots compare simulated and observed biomass across the selected sites using (a) the global and (b) the local sowing date. Colors indicate crop types, and symbols indicate sites. The dashed line represents the 1:1 line. Summary statistics are shown separately for maize, winter wheat,

70 and soybean. Biomass refers to aboveground biomass for maize and soybean, and to total
 71 biomass for winter wheat at Yucheng. No biomass observations were available for Shiyang.

72 The symbols *, **, and *** indicate p values < 0.05 , 0.01 , and 0.001 . Units are t ha^{-1} .

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75 **Figure S3.** As Fig. 5 but for wheat.

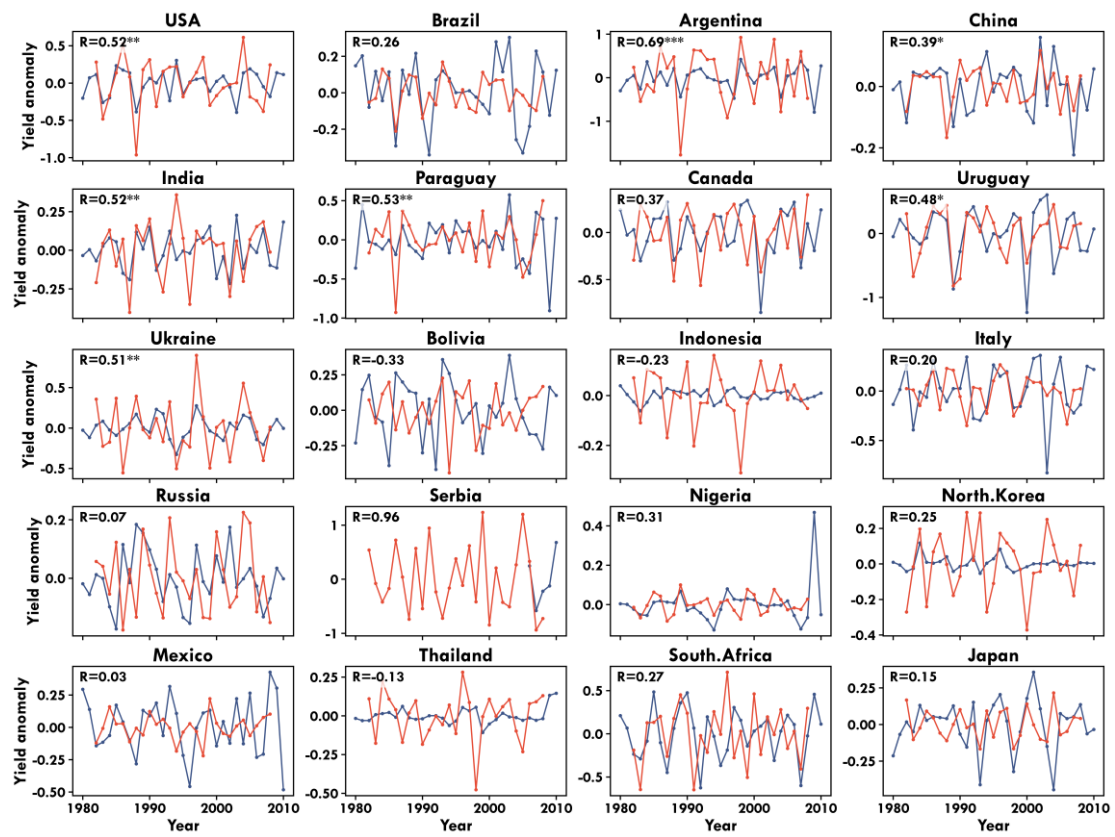


Figure S4. As Fig. 5 but for soybean.

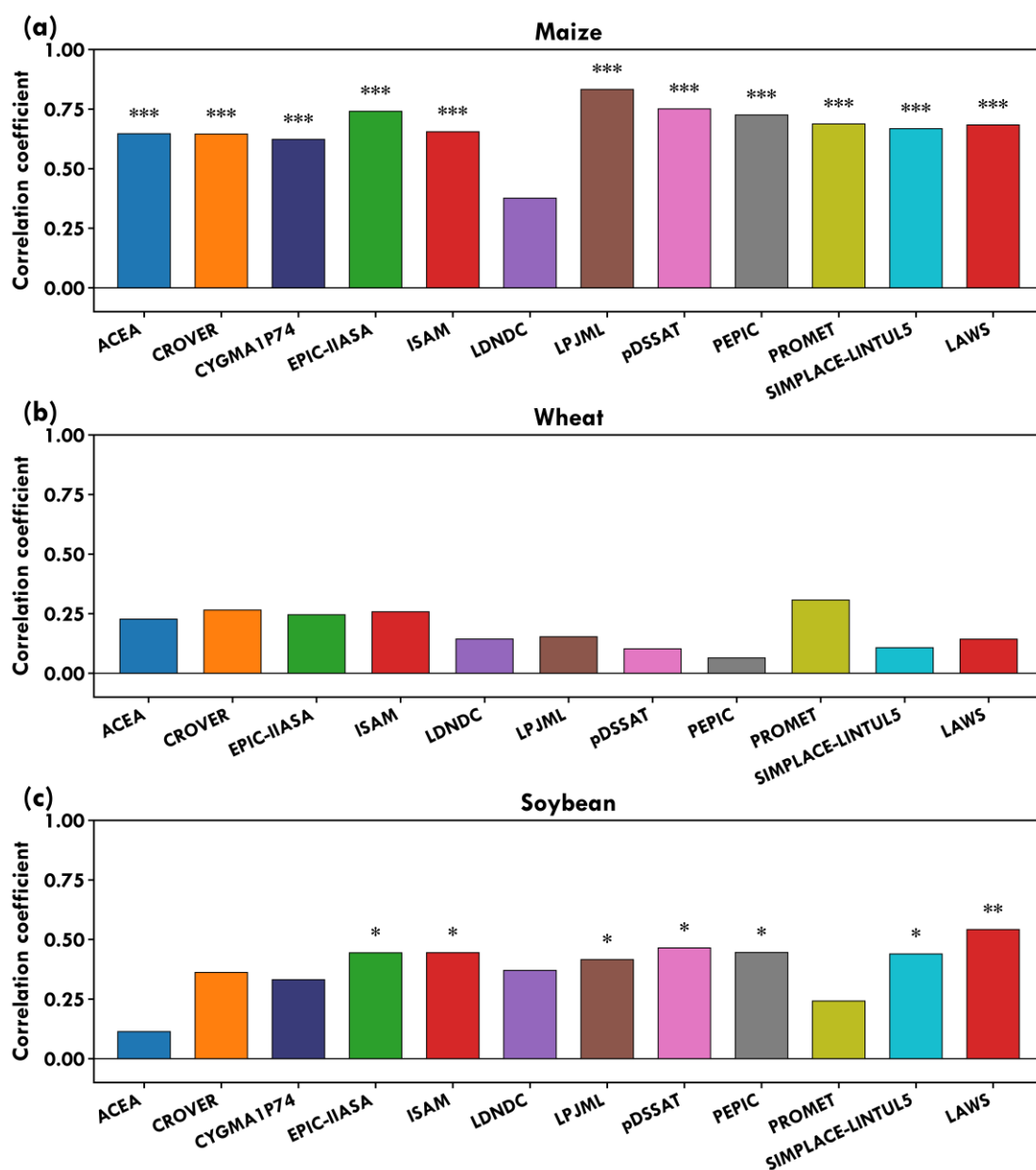


Figure S5. Comparison of correlation coefficients (R) between global yield anomalies simulated by individual GCp3 crop models or LAWS and FAOSTAT yield anomalies during 1982-2008 for (a) maize, (b) wheat, (c) soybean. The wheat yield data of CYGMA1P74 are unavailable.

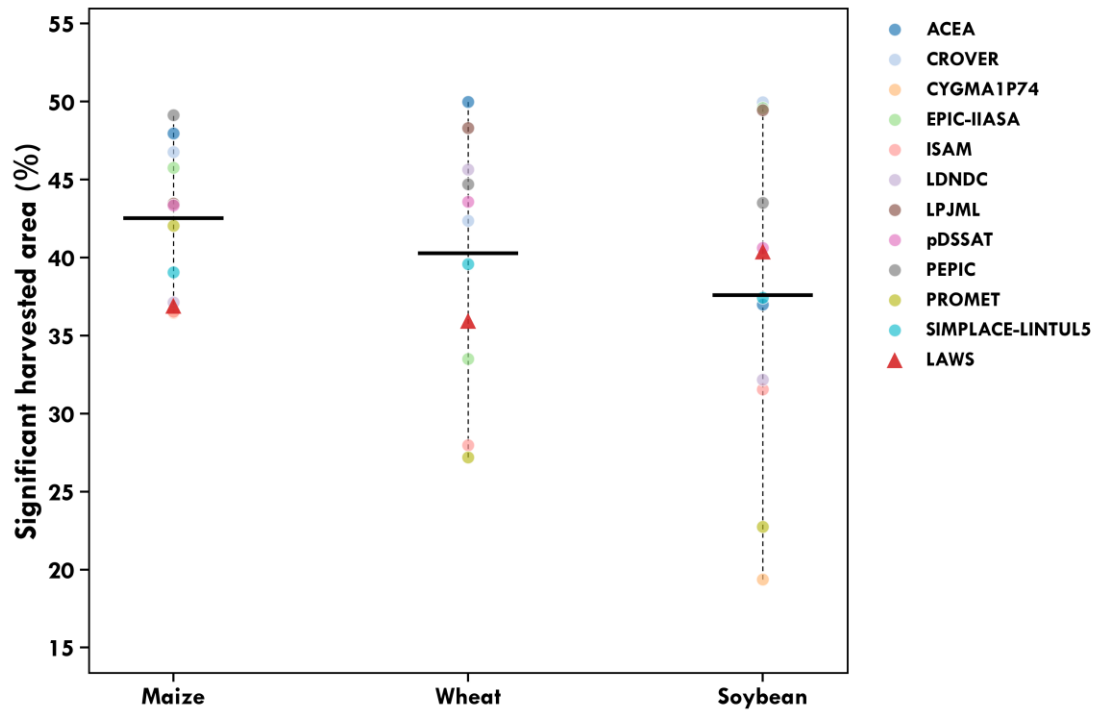


Figure S6. Comparison of the significant harvest-area ratios between simulated and GDHY yield anomalies during 1982-2008 for maize, wheat, and soybean. Black horizontal lines show the GCp3 ensemble means, and dashed vertical lines show the minimum-to-maximum ranges across the GCp3 models. The wheat yield data of CYGMA1P74 are unavailable.

90 **Table S1.** Units of crop-specific parameter used in LAWS.

Parameter abbreviation	Units
HUIS	-
HUG	°C
TO	°C
TB	°C
LAIM	m ² m ⁻²
LAR	-
LAC ₁	-
LAC ₂	-
HIO	-
HIL	-
WA	kg ha ⁻¹ /(MJ m ⁻²)
RUC ₂	-
VPR	kg ha ⁻¹ /(MJ m ⁻²)/kPa
RDR	-
HCM	m
RDM	m
RTF ₁	-
RTF ₂	-
GSM	m s ⁻¹
VPT	kPa
VPC ₁	-
FDM ₁	-
FDM ₂	-

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92 **Table S2.** Application of a 1-year temporal shift to each GCp3 simulated yield series.

Model	1-year shift
ACEA	Yes
CROVER	Yes
CYGMA1P74	Yes
EPIC-IIASA	Yes
ISAM	Yes
LDNDC	Yes
LPJmL	Yes
pDSSAT	Yes
PEPIC	No
PROMET	No
SIMPLACE	No

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94 **Table S3.** Comparison of average annual global irrigation water withdrawals from different
 95 studies.

Data sources	Period	Global Irrigation withdrawals (km ³ yr ⁻¹)	Reference
H08	1984-2013	2544 ± 75	Hanasaki et al. (2008) Hanasaki et al. (2018)
MATSIRO	1983-2007	2158 ± 134	Pokhrel et al. (2012) Pokhrel et al. (2015)
LPJmL	1971-2000	2555	Rost et al. (2008)
PCR-GLOBWB	2000-2015	2644	Wada et al. (2014) Sutanudjaja et al. (2018)
VIC-WUR	1980-2016	2202 ± 60	Droppers et al. (2020)
WaterGAP	1998-2002	3185	Döll et al. (2012) Döll et al. (2014)
Huang et al. (2018)	1980-2010	2327	Huang et al. (2018)
LAWS	1980-2010	2570	This study

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97 **Table S4.** Comparison of average annual global groundwater withdrawals from different
98 studies.

Data sources	Period	Global groundwater withdrawals (km ³ yr ⁻¹)	Reference
H08	1984-2013	789 ± 30	Hanasaki et al. (2018)
MATSIRO	1982-2002	570 ± 61	Pokhrel et al. (2015)
GGW	2001-2020	465-881	Nazari et al. (2025)
PCR-GLOBWB	2000-2015	632	Sutanudjaja et al. (2018)
	2010	952	Wada and Bierkens (2014)
VIC-WUR	1980-2016	992 ± 51	Droppers et al. (2020)
WaterGAP	1998-2002	1519	Döll et al. (2012)
	2000-2009	888	Döll et al. (2014)
LAWS	1980-2010	1055	This study

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