**Supplemental Materials**

**Supplemental Text**

# MATERIALS AND METHODS

## Database formation

Studies containing $\varepsilon_c$ or "radiation use efficiency" in important food crops spanning major plant groups and $C_4$ biofuel crops were found using Web of Science (ISI, Philadelphia, PA, USA; Supplemental Table S1). Articles were mined for information regarding crop husbandry, growing location and conditions, and details regarding $\varepsilon_c$ measurements and calculations. Values and extra information only available in figures were digitized using Grafula 3 version 2.10 (Wesik SoftHaus, St Petersburg, Russian Federation).

Studies were omitted by certain criteria to minimize bias in reported $\varepsilon_c$. Since non-field growth conditions can influence $\varepsilon_c$ (Slattery et al., 2013), experiments not conducted in the field free of enclosure or root barriers were excluded. Studies that included belowground biomass in their measurements (with the exception of peanut and potato, where biomass included the reproductive or vegetative storage structures growing belowground) were also excluded since methods of measuring belowground biomass were less reliable and hugely more variable than aboveground biomass measurements. $\varepsilon_c$ values based on incident radiation were not included due to potential bias caused by changes in interception efficiency (Monteith, 1994). $\varepsilon_c$ values obtained in the presence of intercropping, nutrient deficiency, disease, or other imposed stresses such as elevated atmospheric gases were removed because these factors significantly alter $\varepsilon_c$ (Slattery et al., 2013). If several nutrient treatments were imposed in a study, only the value with the optimal nutrient application was kept for each experiment within the study to avoid depressions in $\varepsilon_c$ due to nutrient limitations. Since $\varepsilon_c$ is often lower in reproductive stages compared to vegetative stages (Sinclair and Muchow, 1999), only values obtained from vegetative stages or the entire growing season were retained. Values from the same study were only kept if they were considered independent (i.e., growth period, location, cultivar, treatment or treatment level differed; Ainsworth et al., 2002). Crops with limited data ($n<40$) were omitted to prevent biased estimates of $\varepsilon_c$.

## Data manipulation and gap filling

$\varepsilon_c$ values were reported in various combinations of units and were standardized to MJ of dry matter per MJ absorbed photosynthetically active radiation (APAR) before analyses. Values with mass units were multiplied by the energy content of the crop tissue type (Table I). If a value encompassed both vegetative and reproductive stages, the mean aboveground plant energy factor was used, whereas values from solely vegetative stages used the energy based on vegetative tissues only (Table I). Radiation values were converted to MJ APAR using the conversion factors reported by Gower et al. (1999) and assuming an average leaf area index of 4.0. Measurements based on intercepted PAR were converted to APAR using a multiplier of 1.04 whereas values based on intercepted solar radiation were multiplied by 1.96 to convert to APAR (Gower et al., 1999).

Despite removing studies containing clearly stressful conditions, there was substantial variation in the recorded weather/climate related conditions that can cause variation in $\varepsilon_c$ (Slattery et al., 2013). These conditions were used as independent variables in multiple regression analyses and included: mean annual [$CO_2$] for the year(s) the experiments were conducted, mean growing season temperature (T), available incident solar radiation during the growing season ($S_t$), and the amount of precipitation (rain and irrigation) available during the growing season ($H_2O$). Mean annual [$CO_2$] data were obtained from Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/). Whenever possible, missing T and $H_2O$ data were obtained from NOAA (www7.ncdc.noaa.gov/CDO/cdo) from the experiment site corresponding to the growing season dates. Missing $S_t$ was found using the National Solar Radiation Database (http://rredc.nrel.gov/solar/old_data/nsrdb/) or the interannual variability data available through NASA SSE (https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi). A genetic component was also included in the analyses and was represented by the year of release (YOR) for each variety for which $\varepsilon_c$ was calculated. Varieties included in the analyses were listed by crop and subgroup (Supplemental Table S2). If an actual YOR was not reported in the literature or the Germplasm Resources Information Network (GRIN) database (National Genetic Resources Program, USDA/ARS), it was stated as the earliest mention in the literature using searches in both Web of Science (ISI, Philadelphia, PA, USA) and Google Scholar. Plant density was also included for maize analyses, both with and without YOR, since significant increases in yield have been correlated with increasing stand density (Duvick, 2005). Groups were assigned within rice and wheat to further investigate means within crops (Table I). The ranges of each independent variable within each crop species and subgroup for the corresponding analyses were listed (Supplemental Table S3).

**Analyses**

All statistical analyses were conducted using Statistical Analysis Software (SAS, ver. 9.3, SAS Institute, Cary, NC, USA). $\varepsilon_c$ means were calculated using an ANOVA (Proc GLM), and differences were considered significant at $p<0.1$. Prior to conducting multiple regression analyses, general relationships between individual independent variables and $\varepsilon_c$ were determined in major crop species. Proc REG was used to determine if relationships were linear or quadratic using the lowest Akaike information criterion (AIC), and to eliminate influential points, the Cook's d metric was used. Next, Proc CORR was used to test for correlation between the independent variables where relationships greater than 0.8 were considered severe. Variance inflation factors were also determined (Proc REG) with the criterion that values greater than 10 also indicated severe correlation. Although significant correlation based on the metrics stated above was not present among any of the independent variables within each crop dataset, partial correlation coefficients were also determined (Proc CORR) for later comparison with multiple regression results (Supplemental Table S4). Multiple regression analyses were conducted on $\varepsilon_c$ versus the independent variables of breeding (YOR) and environmental factors ([$CO_2$], $S_t$, T, and $H_2O$; Proc REG) to determine which factors best explained the variation in $\varepsilon_c$. The lowest corrected AIC ($AIC_c$) score, which adjusted for sample size and was determined from AIC values, was used to identify the best model and rank the individual variables included in the final model. Sample size was drastically reduced in many of the crops when $H_2O$ was included in the model since limited studies reported irrigation amounts. Results were therefore reported for analyses without $H_2O$ unless sample size was reduced by less than 10% with $H_2O$ in the model. This eliminated the only quadratic relationship (rice $\varepsilon_c$ versus $H_2O$) from the analyses, resulting in only linear relationships between $\varepsilon_c$ and the independent variables. The food crops with positive YOR regression coefficients from multiple regression analyses were used to estimate the current $\varepsilon_c$ in 2014, then project the approximate amount of time needed for each crop or subgroup $\varepsilon_c$ to double and to reach the respective theoretical maxima for $C_4$ and $C_3$ plants. This was assuming no changes in climate, breeding intensity, or other factors.

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**Supplementary Table 1.** Data sources used in $\varepsilon_c$ analyses.


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**Supplementary Table 2.**
Varieties included in crop and subgroup analyses.

**Maize**

Adler 30X
B73 x Mo17
Barker
Beck 65X
Beiyu288
Buck Aurora
Buck Austral
Cambel 78
Cargill PAG SX123
Challenger
CM 109
DEA
Dekalb 2F11
Dekalb 3F23
Dekalb 3F24
Dekalb 3S41
Dekalb 4F91
Dekalb 4S80
Dekalb 524
Dekalb 61-69
Dekalb 636
Dekalb DK615
Dekalb DK688
Dekalb DK752
Dekalb DK246
Dekalb DK529
Dekalb Exp164
Dekalb XL72AA
Dekalb XL82
Deltapine G4673B
DK-5219
Dow 2A120
Dow 2B710
Dow 2M545
Eva
F2
F244
F244 x F2
F257
F257 x F244
F286
Funk G-4083
Hycorn 42
Hycorn 53
Hycorn 83
Hyland HL2803
INRA 150
Juanita
King 1131
KW 1074
KWS Domingo
KWS Impacto
KWS Romario
KWS Tandem
LG11
LP
LP x F2
LP x F257
McCurdy 67-14
Mo17
Nidera Ax 599
Nidera Ax 840
Nidera XPA 73811
NK PX9353
NK PX9405
Penjalinan
Pioneer 3245
Pioneer 335
Pioneer 33A14
Pioneer 33P67
Pioneer 3790
Pioneer 3803
Pioneer 3901
Pioneer 3995
Pioneer Brand 35Y67
Pioneer P3540
Pioneer P37P73
Poza Rica 7822
S5154
SNK 2147
SPS 240
Tuxpeño Sequía
Volga
Wis. Hybrid 110
Xianyu335
Z15
Z7
Zhengdan 958

**Sorghum**

*Grain*
87151-3-4/QL36
Argence
ATx378/RTx430
ATx631/RTx2817
Cargill 4462
Cargill 6670
CSH-6
CSH-8
Dekalb DK55
DK46
Hybrid Ramada
IS 27111
IS 27150
Liang Tang Ai
PI 584085
QL39/QL12
Triumph Two 64 Y-G
TX 2862
TX 399
TX 7000
TX 7078
Tx378 x Tx430 Hybrid

*Energy*
Biomass 133
Keller
SF BMR Revolution

**Rice**

*New Hybrids*
IR65564-44-2-2
IR68586-FA-CA-143
IRUBN030055-5-112
IRUBN030055-5-190
IRUBN030055-5-87
IRUBN030056-10-107
IRUBN030056-10-42
IRUBN030062-1-9
IRUBN030063-9-4
IRUBN030070-9-32
Liangyou 293
Liangyoupeijiu
WAB450-I-B-P-38-HB

*Indica*
Huanghuazhan
Il-you 838
IR72
Shanguichao
Shanyou 63
Surin 1
Takanari
Yangdao 6

*Japonica*
Akihikari
Cocodrie
Cypress
HD297
HD502
IR43
IRAT109
JD305
Jefferson
Koshihikari
Labelle
Lemont
Nipponbare
Shinhakaburi
Takenari

*Basmati*
Basmati-2000
Super Basmati

**Wheat**

*Spring*

Americano 26n
Attila
Axona
Bacanora
Bencubbin
Borlaug
Buck Manantial
Buck Nandu
Buck Pucara
Condor
Ente
Eureka FCS
Fielder
Gamenya
Granero INTA
Highbury
HY320
Invento-BAER
Kanred
Klein Favorito
Kulin
Leader
Manu
Maringa
Mexicali
Minaret
Neepawa
Oasis
Oslo
Owens
Pampa INTA
Pandora-INIA
PROINTA Federal
PROINTA Imperial
PROINTA Oasis
PROINTA Pigue
PROINTA Puntal
R143
Sanukinoyume 2000
Saracen
Sonalika
Tammi
Trigomax 200
Vinjett
Weebil
Yecora 70
Yitpi
Zhong

*Winter*

Anza
Aragon 03
Armada
Avalon
Brigadier
Centurk
Cockpit
Estrella
Florida
Galahad
Haven
HD 2285
Hedgehog
Hereward
HP 1633
Huntsman
Hussar
HUW 234
ID-2151
ID-2193
Isengrain
Kaskaskia
Kenong 9204
KN199
Maris Huntsman
Maris Widgeon
Marius
Mercia
Newton
Norman
Pane 247
Pepital
Rialto
Riband
Score
Siete Cerros
Soissons
Stetson
Virtue

**Barley**

Baronesse
Corvette
Gilbert
Grimmett
Inari
Kunnari
Olli
Pearl
Rolf
Scarlett
Steptoe
Theresa
Triumph
Uurainen

**Potato**

Agria
Alpha
Bintje
C14-343
Cara
Cosima
Darwina
Desiree
Diamant
DTO-2
Elles
Escort
Huinkul
Ilam Hardy
Jaerla
Junior
Katahdin
LT-1
Mailen
Maris Piper
Mentor
Pentland Crown
Premiere
Producent
Record Pentland Crown
Spunta

**Peanut**

ASEM 485 INTA
Chibahandachi
Chico
Early Bunch
Flavor Runner 458
Florman INTA
Florunner
Georgia Green
ICGV86031
ICGV86635
ICGV86707
Kadiri 3/Robut 33-1
Manfredi 393 INTA
Mani Pintar
McCubbin
OAC Garroy
OAC Ruby
OAC Tango
Q18801
Tamrun 96
Tifton-8
TMV2
TMV2NLM
VA910212
Virginia Bunch

**Soybean**

| | | | |
|---|---|---|---|
| 93705-34 | Clark | IA 3023 | PI 471938 |
| 93705-36 | CNS | Illini | Pioneer 93B15 |
| A3901RR | Coker 156 | INA | Rend |
| Adams | Coker 368 | Jackson | Resnik |
| Adelphia | Darby | Ks4895 | Roanoke |
| AK (Harrow) | Davis | L17 | Ross |
| Apollo | Durack | Lee | SCE 82-222 |
| Asgrow 3127 | Enrei | Lincoln | Shelby |
| Asgrow A5959 | Essex | Mandell | Spry |
| Benning | Ford | Manokin | Stress Land |
| Boggs | Graham | NC-Roy | Wayne |
| Brand 92M70 | H2L16 | NE3399 | Williams |
| BRS Tracajá | Hawkeye | NTCPR94-5157 | Williams 82 |
| Buchanan | Hsus-H116 | Omaha | Woodworth |
| Calland | Hutcheson | PB-1 | Yudou 22 |
| Century | IA 3010 | PI 416937 | Zane |

**Chick Pea**

| | | | |
|---|---|---|---|
| Amethyst | Borwen | Dwelley | ILC-482 |
| Amit | CDC ChiChi | Evans | ILC-72 |
| Annigeri | CDC Xena | ICC-4958 | Sanford |
| B-90 | CDC Yuma | ILC-202 | Sultano |

**Pigeon Pea**

| | | | |
|---|---|---|---|
| Chaguaramas Pearl | ICPL 84023 | ICPL 88026 | Royes |
| ICP 15027 | ICPL 85010 | ICPL 88032 | UPAS 120 |
| ICP 7179 | ICPL 85037 | ICPL 88039 | UW26 |
| ICPL 1-6 | ICPL 87 | ICPL 89002 | UW17 |
| ICPL 83015 | ICPL 87091 | ICRISAT-1 | |
| ICPL 8357 | ICPL 87119 | No. 418 | |

**Switchgrass**

| | | | |
|---|---|---|---|
| Alamo | Cave-in-Rock | Kanlow | Sunburst |
| Blackwell | Pathfinder | Shawnee | |

**Sugarcane**

| | | | |
|---|---|---|---|
| Co775 | L79-1002 | Q138 | SL8613 |
| H73-6110 | M438/59 | Q96 | SL88116 |
| H78-7234 | NCo376 | SL7103 | SLI121 |
| L7130 | Q117 | SL8306 | |

**Supplementary Table 3.** Independent variable means (top number) and ranges (bottom numbers) from $\varepsilon_c$ regression analyses in six major food crops and $\varepsilon_c$ mean analyses in crop subgroups. Dashes represent unavailable data.

| Species | Sub-group | Independent Variable[a] | | | | | |
|---|---|---|---|---|---|---|---|
| | | YOR (year) | $[CO_2]$ (μmol mol$^{-1}$) | T (ºC) | $S_t$ (MJ m$^{-2}$) | $H_2O$ (mm) | Density (plants m$^{-2}$) |
| Maize | | 1987 | 358 | 20.3 | 2871 | 407 | 8.13 |
| | | 1959-2008 | 340-387 | 12.3-30.3 | 1994-3855 | 28-835 | 2.2-12.2 |
| Sorghum | | 1985 | 363 | 24.0 | 2581 | 314 | -- |
| | | 1961-2011 | 335-390 | 19.2-30.3 | 2052-3120 | 178-1130 | |
| Rice | | 1993 | 376 | 24.8 | 2186 | 819 | -- |
| | | 1966-2010 | 346-390 | 18.2-28.4 | 985-3451 | 227-1500 | |
| | New | 2000 | 383 | 25.8 | 1619 | -- | -- |
| | hybrids | 1984-2010 | 373-390 | 23.1-28.4 | 985-2280 | | |
| | *indica* | 1994 | 383 | 25.2 | 1738 | 1150 | -- |
| | | 1976-2010 | 373-390 | 22.8-28.4 | 1531-2010 | 800-1500 | |
| | *japonica* | 1987 | 370 | 23.5 | 2345 | 1006 | -- |
| | | 1966-2001 | 346-386 | 18.2-25.2 | 1017-3451 | 543-1500 | |
| | Basmati | 1998 | 377 | 26.9 | 3026 | 352 | -- |
| | | 1996-2000 | 377 | 25.4-28.4 | 2958-3102 | 227-520 | |
| Wheat | | 1984 | 366 | 12.3 | 2006 | 359 | -- |
| | | 1912-2010 | 339-390 | 2.22-21.2 | 1140-3026 | 180-748 | |
| | Spring | 1977 | 360 | 13.9 | 2094 | 441 | -- |
| | | 1912-2010 | 339-390 | 8.58-21.2 | 1188-3026 | 180-681 | |
| | Winter | 1987 | 371 | 11.1 | 1903 | 325 | -- |
| | | 1922-2009 | 339-390 | 2.22-22.5 | 1140-3051 | 146-748 | |
| Peanut | | 1982 | 357 | 19.8 | 2547 | 530 | -- |
| | | 1951-2002 | 343-380 | 5.80-27.7 | 1500-3971 | 360-791 | |
| Soybean | | 1986 | 380 | 24.4 | 2558 | 379 | -- |
| | | 1927-2009 | 318-396 | 18.1-28.8 | 1818-3024 | 191-1013 | |

[a] Independent variables included year of release (YOR), mean annual $CO_2$ concentration ($[CO_2]$) during the measurement period, mean growing season temperature (T), and available solar radiation during the growing season ($S_t$). Water available as precipitation and irrigation ($H_2O$) was included when sample size changed by less than 10% after including it in the analyses. Density was only analyzed in maize.

**Supplementary Table 4.** Partial correlation coefficients (top number) and significance level (bottom number) of independent variables when linearly regressed upon $\varepsilon_c$ in six major food crops. Dashes represent inapplicable or unavailable data.

| | Independent Variable[a] | | | | | |
|---|---|---|---|---|---|---|
| | YOR | $[CO_2]$ | $S_t$ | T | $H_2O$ | Density |
| Peanut | 0.278 | 0.0669 | -0.220 | 0.442 | -- | -- |
| (n=51) | 0.056 | 0.65 | 0.13 | 0.0016 | -- | -- |
| Soybean | 0.161 | 0.290 | -0.538 | -0.496 | 0.0649 | -- |
| (n=117) | 0.088 | 0.0018 | <.0001 | <.0001 | 0.49 | -- |
| Rice | 0.101 | -0.0154 | -0.806 | -0.316 | -- | -- |
| (n=102) | 0.32 | 0.88 | <.0001 | 0.0015 | -- | -- |
| Wheat | 0.170 | -0.0423 | -0.128 | -0.237 | -- | -- |
| (n=159) | 0.034 | 0.60 | 0.11 | 0.0029 | -- | -- |
| Sorghum | 0.173 | 0.266 | -0.485 | 0.268 | -- | -- |
| (n=23) | 0.47 | 0.26 | 0.030 | 0.25 | -- | -- |
| Maize | 0.204 | -0.0775 | 0.105 | 0.0372 | -- | -0.0439 |
| (n=149) | 0.014 | 0.35 | 0.21 | 0.66 | -- | 0.60 |

**[a]** Independent variables included year of release (YOR), mean annual $CO_2$ concentration ($[CO_2]$) during the measurement period, mean growing season temperature (T), and available solar radiation during the growing season ($S_t$). Water available as precipitation and irrigation ($H_2O$) was included when sample size changed by less than 10% after including it in the analyses. Density was only analyzed in maize.