

New Phytologist Supporting Information to “Carboniferous plant physiology breaks the mold” by Jonathan P. Wilson, Joseph D. White, Isabel P. Montañez, William A. DiMichele, Jennifer C. McElwain, Christopher J. Poulsen and Michael T. Hren.

Accepted November 17, 2019.

Table S1 - Values and sources of maximum theoretical water vapor conductance (g_{wmax} ; mol m⁻² s⁻¹) for representative species of Carboniferous flora based on anatomical measurements applied to Equation 1. These data are the most current and complete analyses of these species in our dataset. These values are plotted as violin plots (Figure 2) and statistical summaries (Table 1) in the main text.

Group	Species	g_{wmax} (mol m ⁻² s ⁻¹)	Reference
Medullosans	<i>Alethopteris lesquereuxii</i>	2.30	Reihman and Schabillion (1976)
	<i>Alethopteris sullivanii</i>	4.71	Stidd and Stidd (1976)
	<i>Blanziopteris praedentata</i>	5.15	Krings and Kerp (1999)
	<i>Laveinopteris loshii</i>	1.68	Cleal and Shute (1992)
	<i>Laveinopteris tenuifolia</i>	2.80	Shute and Cleal (2002)
	<i>Lescuropteris genuina</i>	0.64	Krings and Kerp (1997)
	<i>Macroneuropteris scheuchzeri</i>	1.02	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.64	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.20	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	2.08	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.04	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.22	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.05	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.60	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	0.68	Montañez et al. (2016)

	<i>Macroneuropteris scheuchzeri</i>	1.02	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.28	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.47	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.64	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.78	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.53	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.40	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.33	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.47	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.53	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.31	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.35	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.72	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.77	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.69	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	2.08	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.77	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.76	Montañez et al. (2016)

	<i>Macroneuropteris scheuchzeri</i>	1.88	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.59	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.34	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.71	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.63	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	1.75	Montañez et al. (2016)
	<i>Macroneuropteris scheuchzeri</i>	0.84	Montañez et al. (2016)
	<i>Neuropteris aconiensis</i>	0.16	Cleal and Zodrow (1989)
	<i>Neuropteris britannica</i>	0.59	Cleal and Zodrow (1989)
	<i>Neuropteris flexuosa</i>	0.62	Cleal and Zodrow (1989)
	<i>Neuropteris loshii</i>	0.91	Cleal and Zodrow (1989)
	<i>Neuropteris macrophylla</i>	0.29	Cleal and Zodrow (1989)
	<i>Neuropteris obliqua</i>	0.66	Krings and Kerp (1999)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.88	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.54	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.44	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.49	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.17	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.24	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.36	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.21	Cleal and Zodrow (1989)

	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.02	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.31	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.50	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.64	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>aconiensis</i>	1.51	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	1.34	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	1.13	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	1.17	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	1.14	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	1.46	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>sarana</i>	0.18	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>simonii</i>	0.52	Cleal and Zodrow (1989)
	<i>Neuropteris ovata</i> var. <i>simonii</i>	1.84	Cleal and Zodrow (1989)
	<i>Neuropteris rarinervis</i>	0.81	Cleal and Zodrow (1989)
	<i>Neuropteris scheuchzeri</i>	0.40	Cleal and Zodrow (1989)
	<i>Neuropteris</i> sp. 1	1.27	Cleal and Zodrow (1989)
	<i>Neuropteris</i> sp. 2	0.82	Cleal and Zodrow (1989)
	<i>Neuropteris subauriculata</i>	0.53	Cleal and Zodrow (1989)
	<i>Neuropteris tenuifolia</i>	1.36	Cleal and Zodrow (1989)
	<i>Reticulopteris germarii</i>	1.74	Zodrow and Cleal (1993)
	<i>Reticulopteris germarii</i>	1.74	Zodrow and Cleal (1993)
Minimum		0.16	

Maximum		5.15	
Median		1.36	
Mean		1.42	
Sphenopsids	<i>Sphenophyllum apiciserratum</i>	0.257	Yao et al. (2000)
	<i>Sphenophyllum emarginatum</i>	1.241	Batenburg (1981, 1982)
	<i>Sphenophyllum emarginatum</i>	0.712	Batenburg (1981)
	<i>Sphenophyllum emarginatum</i>	0.463	Batenburg (1981)
	<i>Sphenophyllum emarginatum</i>	1.049	Batenburg (1981)
	<i>Sphenophyllum emarginatum</i>	0.714	Batenburg (1981)
	<i>Sphenophyllum emarginatum</i>	0.546	Batenburg (1981)
	<i>Sphenophyllum koboense</i>	0.180	Yao et al. (2000)
	<i>Sphenophyllum miravallis</i>	0.540	Hettterscheid and Batenburg (1984)
	<i>Sphenophyllum miravallis</i>	0.540	Hettterscheid and Batenburg (1984)
	<i>Sphenophyllum</i> sp. [dispersed]	0.431	Šimůnek (2015)
	<i>Sphenophyllum</i> sp. [dispersed]	0.338	Šimůnek (2015)
	<i>Sphenophyllum</i> sp. [dispersed]	0.398	Šimůnek (2015)
	<i>Sphenophyllum</i> sp. [dispersed]	0.311	Šimůnek (2015)
	<i>Sphenophyllum speciosum</i>	0.112	Pant and Mehra (1963)
	<i>Sphenophyllum speciosum</i>	0.218	Pant and Mehra (1963)
Minimum		0.11	
Maximum		1.24	

Median		0.45	
Mean		0.50	
Lycopsids	<i>Bothrodendron minutifolium</i>	2.67	Thomas BA (1967)
	<i>Bothrodendron punctatum</i>	4.44	Thomas BA (1967)
	<i>Lepidodendron aculeatum</i>	3.35	Thomas BA (1970)
	<i>Lepidodendron aculeatum</i>	3.72	Thomas BA (1970)
	<i>Lepidodendron arberi</i>	3.66	Thomas BA (1970)
	<i>Lepidodendron dichotomum</i>	7.78	Thomas BA (1970)
	<i>Lepidodendron dichotomum</i>	8.52	Thomas BA (1966)
	<i>Lepidodendron feistmanteli</i>	5.61	Thomas BA (1970)
	<i>Lepidodendron loricatum</i>	3.79	Thomas BA (1966)
	<i>Lepidodendron mannabachense</i>	2.22	Thomas BA (1970)
	<i>Lepidodendron obovatum</i>	4.65	Thomas BA (1966)
	<i>Lepidodendron peachii</i>	3.60	Thomas BA (1970)
	<i>Lepidodendron rhodianum</i>	1.23	Thomas BA (1970)
	<i>Lepidodendron subdichotomum</i>	3.73	Thomas BA (1970)
	<i>Lepidodendron veltheimii</i>	2.56	Thomas BA (1970)
	<i>Lepidophloios acadianus</i>	2.95	Thomas BA (1977)
	<i>Lepidophloios acerosus</i>	3.20	Thomas BA (1977)
	<i>Lepidophloios grangeri</i>	3.28	Thomas BA (1977)
	<i>Lepidophloios laricinus</i>	5.47	Thomas BA (1977)
	<i>Lepidophloios macrolepidotus</i>	1.02	Thomas BA (1977)
	<i>Ulodendron landsburgii</i>	1.13	Thomas BA (1968)
	<i>Ulodendron landsburgii</i>	2.19	Thomas BA (1968)
	<i>Ulodendron landsburgii</i>	3.55	Thomas BA (1968)
	<i>Ulodendron landsburgii</i>	4.37	Thomas BA (1968)
	<i>Ulodendron landsburgii</i>	5.94	Thomas BA (1968)
	<i>Ulodendron majus</i>	4.28	Thomas BA (1967)

	<i>Ulodendron majus</i>	8.30	Thomas BA (1967)
Minimum		1.02	
Maximum		8.52	
Median		3.66	
Mean		3.97	
Cordaitaleans	<i>Cordaabaxicutis boleslawii</i>	1.59	Šimůnek and Florjan (2013)
	<i>Cordaabaxicutis borassifolioides</i>	4.44	Šimůnek and Florjan (2013)
	<i>Cordaabaxicutis gorae</i>	3.13	Šimůnek and Florjan (2013)
	<i>Cordaabaxicutis papilloborassifolius</i>	6.50	Šimůnek and Florjan (2013)
	<i>Cordaabaxicutis sierszae</i>	2.21	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis bracteatus</i>	0.48	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis carpaticus</i>	0.09	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis janinae</i>	0.11	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis krawjewskae</i>	0.06	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis laziskae</i>	1.98	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis papillostomatus</i>	0.29	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis pussilostomatus</i>	0.31	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis tectostomatus</i>	0.06	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis zalezensis</i>	0.16	Šimůnek and Florjan (2013)
	<i>Cordaadaxicutis zoldanii</i>	0.31	Šimůnek and Florjan (2013)
	<i>Cordaites borassifolius</i>	0.14	Šimůnek (2007), Šimůnek et al. (2009)
	<i>Cordaites pilsensis</i>	0.57	Šimůnek (2007)
	<i>Cordaites principalis</i> type 2	1.99	Zodrow et al. (2000)
	<i>Cordaites rerichensis</i>	1.62	Šimůnek (2007)

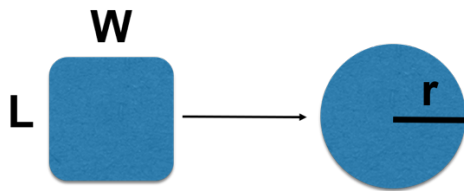
Minimum		0.06	
Maximum		6.50	
Median		0.48	
Mean		1.37	
Tree Ferns	<i>Acitheca polymorpha</i>	0.40	Pšenička (2005)
	<i>Diplazites unitus</i>	0.06	Pšenička (2005)
	<i>Diplazites unitus</i>	0.08	Pšenička (2005)
	<i>Lobopteris aspidioides</i>	1.05	Pšenička (2005)
	<i>Lobopteris miltonii</i>	0.35	Pšenička (2005)
	<i>Lobopteris miltonii</i>	0.36	Pšenička (2005)
	<i>Lobopteris polypodioides</i>	0.34	Pšenička (2005)
	<i>Lobopteris polypodioides</i>	0.26	Pšenička (2005)
	<i>Pecopteris aspidioides</i>	1.01	Pšenička et al. (2005)
	<i>Pecopteris aspidioides</i>	2.00	Pšenička et al. (2005)
	<i>Pecopteris cf. micromiltonii</i>	0.12	Pšenička (2005)
	<i>Pecopteris cyathea</i>	0.05	Pšenička (2005)
	<i>Pecopteris miltonii</i>	0.17	Pšenička et al. (2005)
	<i>Pecopteris miltonii</i>	1.57	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	1.97	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	1.97	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	1.10	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	1.10	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	0.23	Pšenička et al. (2005)
	<i>Pecopteris nyranensis</i>	0.23	Pšenička et al. (2005)
	<i>Pecopteris polipodioides</i>	0.16	Pšenička et al. (2005)
	<i>Pecopteris polipodioides</i>	0.32	Pšenička et al. (2005)
	<i>Senftenbergia plumosa</i>	0.89	Psenicka and Bek (2003)
	<i>Senftenbergia plumosa</i>	0.89	Psenicka and Bek (2003)
	<i>Sydneia manleyi</i>	0.27	Pšenička et al. (2003)

Minimum		0.05	
Maximum		2.00	
Median		0.35	
Mean		0.68	

Methods S1

Converting tracheid cross-sectional area to area of an equivalent circle

The shape of tracheids in plants, when viewed in cross-sectional perspective, can occasionally more closely resemble a square with rounded corners rather than a circle, which complicates the calculation of hydraulic resistance (see Wilson and Fischer, 2011, for further discussion). To solve this problem, tracheids with oblong shapes can have their cross-sectional area calculated and their diameter expressed as a circle with equivalent area, represented visually here:



$$L \times W = \pi r^2$$

Tracheid length and width are measured directly from plant material and the resulting equation is solved for the radius, which is doubled to find the diameter of the equivalent circle.

Difference between maximum theoretical stomatal conductance (g_{wmax}) and average operational stomatal conductance (g_s)

It is quite important to define stomatal conductance in any text because there are frequently multiple expressions used to mean different terms. For example, in this paper, we use theoretical maximum stomatal conductance based on anatomy (g_{wmax} ; Equation 1) as compared with operational maximum stomatal conductance from living plants based on porometry or infrared gas analysis (and porometry values can often exceed values derived from infrared gas analysis; see Murray et al. 2019), as further compared with average operational stomatal conductance (g_s). The third term can be derived from the first term using the equation below (Franks et al. 2014; McElwain et al. 2016):

$$g_s = 0.2 \times g_{wmax}$$

Notes S1

Addressing a number of small issues raised by B&Z 2019.

How can plants function with high stomatal conductance and low cavitation resistance?

Contrary to Boyce and Zwieniecki’s assertion, there is no contradiction between plants with high stomatal conductance and low cavitation resistance, such as the medullosans: these plants would be expected to fix large amounts of carbon for the period of time in which abundant soil water is available—a well-adapted physiology to the tropical everwet environments in which medullosans are ecologically important during the Carboniferous. A plant with relatively low stomatal conductance and high stem conductivity, such as *Sphenophyllum*, would be well-adapted to a *high-light*, open environment—precisely the realm occupied by the ground cover and/or scrambling sphenophyte. In turn, plants with low cavitation resistance and high stomatal conductance would be vulnerable to any environmental change that increased the probability and frequency of droughts, which is precisely the type of change observed during the latest Pennsylvanian and early Permian, in which many medullosans and high-conductance plants suffered extinction in North America.

Stomatal conductance acceleration?

Publishing and typesetting errors happen. For example, consider this table, from Boyce et al. 2009:

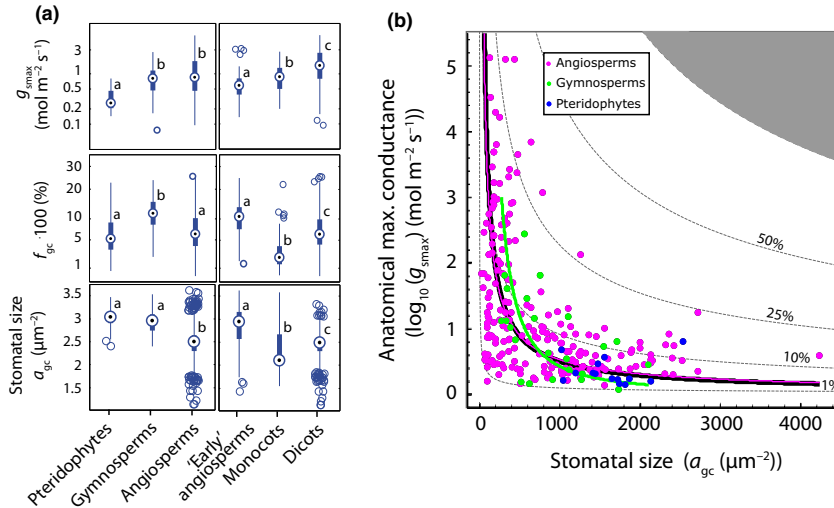
Table 2: Maximum stomatal conductance and vein density.

Species	Conductance (mol H ₂ O/m ² s ²)	St. dev.	Vein density (mm/mm ²)	St. dev.
FERNS				
<i>Lygodium venustum</i>	0.1090	0.0234	2.77	0.73
<i>Tectaria confluens</i>	0.0738	0.0183	1.29	0.12
<i>Dipteris conjugata</i>	0.1703	0.0269	4.36	0.43
<i>Bolbitis portoricensis</i>	0.0665	0.0300	1.47	0.20
<i>Polypodium triseriale</i>	0.0449	0.0155	0.95	0.17
<i>Pteris altissima</i>	0.1363	0.0271	1.80	0.23
CONIFERS				
<i>Agathis robusta</i>	0.062	0.011	1.19	0.17
<i>Nageia nagi</i>	0.0908	0.0510	1.78	0.58
ANGIOSPERMS				
<i>Eucalyptus globules</i>	0.3592	0.0621	9.40	0.78
<i>Byrsonema crassifolia</i>	0.4488	0.0436	15.36	1.37
<i>Curatela Americana</i>	0.3743	0.0415	16.16	2.88
<i>Dalbergia retusa</i>	0.6619	0.0650	13.45	0.94
<i>Genipa Americana</i>	0.4161	0.0425	10.60	0.82
<i>Rhedera trinervis</i>	0.4118	0.0879	11.07	0.36
<i>Bedfordia salicina</i>	0.2500	0.0349	5.70	0.49
<i>Amborella trichopoa</i>	0.1800	0.0380	2.28	0.15
<i>Simarouba glauca</i>	0.6020	0.0480	14.80	1.81
<i>Pharus lappulacius</i>	0.1348	0.0207	2.90	0.14
<i>Hyparrhenia rufa</i>	0.3885	0.0863	11.28	1.47

At first glance, it appears that the authors created two new taxa with capitalized species names (“*Curatela Americana*” and “*Genipa Americana*”) and, furthermore, created a new term for plant physiologists. Rather than expressing stomatal conductance to water as a volume of water as a function of area and time (mol H₂O m⁻²s⁻¹), they appear to have derived a new term: **stomatal conductance acceleration**, where they have expressed the volume of water lost as a **rate of change** of stomatal conductance (mol H₂O m⁻²s⁻²). One way to remark on this would be to express that perhaps this new measurement will find some use in the future. However, a more charitable explanation would be to read this in a paper, recognize the authors’ intent, and chalk it up to a typesetting error. Most scientists, knowing that we live in glass houses and are at the

mercy of a slip of the keyboard at any time, would take the second path. However, Boyce and Zwieniecki’s *Viewpoint* demonstrates that their oversight should be pointed out.

Another example of a typesetting error can be found in de Boer et al. 2016 (a *New Phytologist* publication), in their Figure 4.



In the upper panels of section (a), g_{smax} in pteridophytes, gymnosperms, and angiosperms is plotted with a linear y-axis, but in panel (b), it is plotted along the y-axis in what is labeled a logarithmic plot. These two axes span the same numerical range but are mutually irreconcilable—either (b) should be a linear plot and this was a typesetting error, or—less likely, given the range of plausible values—(a) should also be a logarithmic plot. But because the authors of this paper did not publish their raw stomatal conductance values, as we have since 2016 and continue here—despite de Boer et al. being a “Research” paper and not an invited review—these plots cannot be reconciled.

We reiterate that small errors can be found in nearly every scientific publication and include these examples to highlight how common they are.

B&Z lack an elementary understanding of geological modeling: vegetation simulations using a general circulation model are not “carbon cycle” models

A further major area of misunderstanding is Boyce and Zwieniecki’s assertion that we have combined a ‘Berner-style carbon cycle model’ with a regional biome model. This belief on their part is the reason they link the Montañez et al. (2016) and the Wilson et al. (2017) papers and is fundamentally erroneous. Boyce and Zwieniecki (2019) state “In addition to climate, the other original application of the physiological interpretations expanded upon in Wilson et al. (2017) was to the modeling of the Carboniferous *carbon cycle* (Montañez et al., 2016).” We are perplexed by this assertion as in neither paper did we introduce, utilize, or refer to a carbon cycle model. The results and discussion of terrestrial carbon sequestration in the Montañez et al. (2016) paper (and not a topic discussed in the Wilson et al. (2017) paper) are based on vegetation simulations made using GENESIS, a General Circulation Model v. 3.0 linked to an ice-sheet model — also without a carbon cycle model (Horton et al., 2010). As we state in the main text, the discussion in Montañez et al. (2016) of the potential of late Paleozoic plants — lycopsids in particular — to sequester

sufficient carbon during the glacial stages of eccentricity cycles relative to the interglacial stages, and thus to impart large-scale (100 to 200 ppm) changes in atmospheric $p\text{CO}_2$ between glacials and interglacials, is based on the productivity and lifespan estimates of Boyce and DiMichele (2016). The reconstructed fossil plant water-use efficiency values presented in Fig. 3 of Montañez et al. (2016), which Boyce and Zwieniecki (2019) suggest was an *integral part of the carbon modeling*, have nothing to do with the GCM modeling or the associated results. Our modeling approach and methods were laid out explicitly in the 62-page Supplementary Online Materials of Montañez et al. (2016). The primary point of Boyce and Zwieniecki’s section ‘Fossil plants as components of the Earth system’—that plants strengthened the feedback between rock weathering and atmospheric CO_2 —is one that has been made by many previously published papers, and several introductory geology textbooks, over the past few decades. The relevance of this point to the Montañez et al. (2016) and the Wilson et al. (2017) papers remains puzzling. Furthermore, we note that Boyce is an author on a recent publication that directly contradicts the view presented in B&Z 2019: “Land plant evolution decreased, rather than increased, weathering rates” states ‘that land plant evolution decreased the global silicate weathering flux through their increase of organic carbon burial.’

References S1

- Batenburg, L.H. 1981. Vegetative anatomy and ecology of *Sphenophyllum zwickaviense*, *S. emarginatum*, and other “compression species” of *Sphenophyllum*. *Review of Palaeobotany and Palynology* 32:275-313.
- Batenburg LH. 1982. “Compression species” and “petrification species” of *Sphenophyllum* compared. *Review of Palaeobotany and Palynology* 36: 335–359.
- Boyce CK, Brodrribb TJ, Feild TS, Zwieniecki MA. 2009. Angiosperm leaf vein evolution was physiologically and environmentally transformative. *Proceedings of the Royal Society B: Biological Sciences*, 276(1663):1771-1776.
- Boyce CK, Zwieniecki, MA. 2019. *Viewpoint* — The prospects for constraining productivity through time with the whole-plant physiology of fossils. *New Phytologist* 233:40-49.
- Cleal CJ, Shute CH. 1992. Epidermal features of some Carboniferous neuropteroid fronds. *Review of Palaeobotany and Palynology* 71: 191–206.
- Cleal CJ, Zodrow EL. 1989. Epidermal structure of some medullosan *Neuropteris* foliage from the Middle and Upper Carboniferous of Canada and Germany. *Palaeontology* 32: 837–882.
- de Boer HJ, Price CA, Wagner-Cremer F, Dekker SC, Franks PJ, Veneklaas EJ. 2016. Optimal allocation of leaf epidermal area for gas exchange. *New Phytologist* 210(4): 1219-1228.
- Franks PJ, Royer DL, Beerling DJ, Van de Water PK, Cantrill DJ, Barbour MM, Berry JA. 2014. New constraints on atmospheric CO_2 concentration for the Phanerozoic. *Geophysical Research Letters* 41(13): 4685-4694.
- Hetterscheid WLA, Batenburg LH. 1984. *Sphenophyllum miravallis* Vetter and *Bowmanites cupulatus* sp.n. from the “Illinger Flözzone” (“Heusweiler Schichten”, Lower Stephanian, Saar Basin, German Federal Republic). *Review of Palaeobotany and Palynology* 40: 263–293.

- Horton DE, Poulsen CJ, Pollard D. 2010. Influence of high-latitude vegetation feedbacks on late Palaeozoic glacial cycles. *Nature Geoscience* 3:1–6.
- Krings M, Kerp H. 1997. Cuticles of *Lescuropteris genuina* from the Stephanian (Upper Carboniferous) of Central France: evidence for a climbing growth habit. *Botanical Journal of the Linnean Society* 123: 73–89.
- Krings M, Kerp H. 1999. Morphology, growth habit, and ecology of *Blanziopteris praedentata* (Gothan) nov. comb., a climbing neuropteroid seed fern from the Stephanian of Central France. *International Journal of Plant Sciences* 160: 603–619.
- McElwain JC, Yiotis C, Lawson T. 2016. Using modern plant trait relationships between observed and theoretical maximum stomatal conductance and vein density to examine patterns of plant macroevolution. *New Phytologist* 209(1): 94–103.
- Montañez IP, McElwain JC, Poulsen CJ, White JD, DiMichele, WA, Wilson JA, Griggs G, Hren M. 2016. Climate, $p\text{CO}_2$ and terrestrial carbon cycle linkages during late Palaeozoic glacial-interglacial cycles. *Nature Geoscience* 9: 824–828.
- Murray M, Soh WK, Yiotis C, Batke S, Parnell A, Spicer RA, Lawson T, Caballero R, Wright IJ, Purcell C, McElwain JC. 2019. Convergence in maximum stomatal conductance of C3 woody angiosperms in natural ecosystems across bioclimatic zones. *Frontiers in Plant Science* 10:558.
- Pšenička, J., J. Bek, E.L. Zodrow, C.J. Cleal, and A.R. Hemsley. 2003. A new late Westphalian fossil marattialean fern from Nova Scotia. *Botanical Journal of the Linnean Society* 142:199–212.
- Pšenička J, Bek J. 2003. Cuticles and spores of *Senftenbergia plumosa* (Artis) Bek and Pšenička from the Carboniferous of Pilsen Basin, Bohemian Massif. *Review of Palaeobotany and Palynology* 125: 299–312.
- Pšenička, J., 2005. Taxonomy of Pennsylvanian-Permian ferns from coal basins in the Czech Republic and Canada. 183 pp. Partially published Ph.D. thesis, Faculty of Science, Charles University, Prague, Czech Republic.
- Pšenička, J., E.L. Zodrow, M. Mastalerz, J. Bek. 2005. Functional groups of fossil marattialeans: chemotaxonomic implications for Pennsylvanian tree ferns and pteridophylls. *International Journal of Coal Geology* 61:259–280.
- Reihman MA, Schabillion JT. 1976. Cuticles of two species of *Alethopteris*. *American Journal of Botany* 63: 1039–1046.
- Shute CH, Cleal CJ. 2002. Ecology and growth habit of *Laveineopteris*: A gymnosperm from the Late Carboniferous tropical rain forests. *Palaeontology* 45: 943–972.
- Šimůnek, Z., 2007. New classification of the genus *Cordaites* from the Carboniferous and Permian of the Bohemian Massif based on micromorphology of its cuticle. *Acta Musei Nationalis Pragae, Series B Historia Naturalis* 62:97–210.
- Šimůnek, Z., S. Opluštiland, J. Drábková., 2009. *Cordaites borassifolius* (Sternberg) Unger (Cordaitales) from the Radnice Basin (Bolsovian, Czech Republic). *Bulletin of Geosciences* 84:301–336.

- Šimůnek, Z., and S. Florjan. 2013. The Pennsylvanian cordaitalean dispersed cuticles from the Upper Silesian Basin (Poland). *Review of Palaeobotany and Palynology* 197:26-49.
- Šimůnek, Z., and J. Bureš. 2015. Dispersed cuticles and conducting tissue of *Sphenophyllum* BRONGNIART from the Westphalian D of Kalinovo, Donets Basin, Ukraine. *Geologia Croatica* 68:1-9.
- Stidd LLO, Stidd BM. 1976. Paracytic (Syndetocheilic) stomata in Carboniferous seed ferns. *Science* 193: 156–157.
- Thomas, B.A. 1966. The cuticle of the Lepidodendroid stem. *New Phytologist* 65:296-303.
- Thomas, B.A. 1967. The cuticle of two species of *Bothrodendron* [Lycopsida: Lepidodendrales]. *Journal of Natural History* 1:53-60.
- Thomas, B.A. 1968. The carboniferous fossil lycopod *Ulodendron landsburgii* (Kidston) comb. nov. *Journal of Natural History* 2:425-428.
- Thomas, B.A. 1970. Epidermal studies in the interpretation of *Lepidodendron* species. *Paleontology* 13:145-173.
- Thomas, B.A. 1977. Epidermal studies in the interpretation of *Lepidoploios* species. *Paleontology* 20:273-293.
- Wilson JP, Fischer WW. 2011. Hydraulics of *Asteroxylon mackiei*, an early Devonian vascular plant, and the early evolution of water transport tissue in terrestrial plants. *Geobiology* 9: 121-130.
- Wilson JP, Montañez IP, White JD, DiMichele WA, McElwain JC, Poulsen CJ, Hren MT. 2017. *Tansley Review* — Dynamic Carboniferous tropical forests: New views of plant function and potential for physiological forcing of climate. *New Phytologist* 215:1333-1353.
- Zodrow EL, Cleal CJ. 1993. The epidermal structure of the Carboniferous gymnosperm frond *Reticulopteris*. *Palaeontology* 36: 65–79.
- Zodrow EL, Šimůnek Z, Bashforth AR. 2000. New cuticular morphotypes of *Cordaites principalis* from the Canadian Carboniferous Maritimes Basin. *Canadian Journal of Botany* 78: 135–148.