Appendix A

400 MILLION YEARS OF SILICA BIOMINERALIZATION IN LAND PLANTS

Abstract

Biomineralization plays a fundamental role in the global silicon cycle. Grasses are known to mobilize significant quantities of Si in the form of silica biominerals, and dominate the terrestrial realm today, but have relatively recent origins and only rose to taxonomic and ecological prominence within the Cenozoic Era. This raises questions regarding when, and how, the biological silica cycle evolved. To address these questions, we examined silica abundances of extant members of early-diverging land plant clades, which show silica biomineralization is widespread across terrestrial plant linages. Particularly high silica abundances are observed in lycophytes and early-diverging ferns. However, silica biomineralization is rare within later evolving gymnosperms, implying a complex evolutionary history within the seed plants. Electron microscopy and x-ray spectroscopy show that the most common silica-mineralized tissues include the vascular system, epidermal cells, and stomata—consistent with the hypothesis that biomineralization in plants is frequently coupled to transpiration. Furthermore, sequence, phylogenetic, and structural analysis of nodulin 26-like intrinsic proteins (NIPs) from diverse plant genomes points to a plastic and ancient capacity for silica accumulation within terrestrial plants. The integration of these two comparative biology approaches demonstrates that silica biomineralization has been an important process for land plants over their > 400 myr evolutionary history.

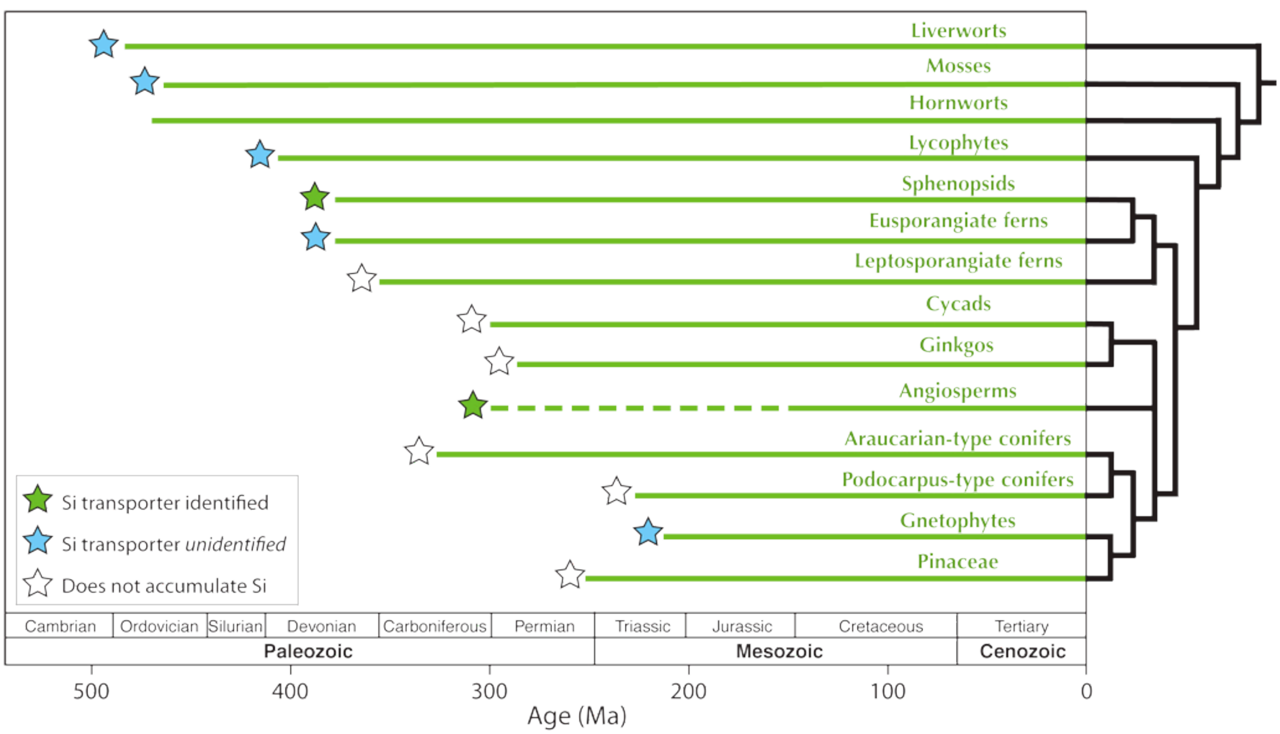
Introduction

In modern ecosystems, land plants play a major role in the silica cycle through the accumulation and synthesis of silica, an amorphous biomineral composed of SiO_2, known as phytoliths or silica bodies. It is widely appreciated that actively accumulating plants such as grasses are important components of the terrestrial biological pump of silica (Carey & Fulweiler 2012; Conley 2002; Epstein 1994). Plant silica also plays a key role in connecting the terrestrial and marine carbon cycles, because silica is an important nutrient for marine silica-biomineralizing primary producers (i.e. diatoms) (Conley 2002; Epstein 1994; Falkowski et al. 2004; Frings et al. 2014; Raven 1983; Raven 2003). However, both grasses and diatoms evolved in the latter part of the Mesozoic Era (Edwards et al. 2010; Harper & Knoll 1975; Philippe et al. 1994) and rose to ecological dominance within the Cenozoic Era (Edwards et al. 2010; Falkowski et al. 2004; Katz et al. 2004; Stromberg 2004; Stromberg 2005; Stromberg & Feranec 2004). Determining precisely when, and how, the terrestrial-marine silica teleconnections evolved remain obstacles to reconstructing the history of the silica cycle.

Direct analysis of silica bodies in the fossil record provides limited insight into this problem. When fossiliferous material is macerated, it is often challenging to identify whether residual silica bodies are the result of primary biomineralization or secondary diagenetic processes, and if a living plant origin is suspected, it is often difficult to assign taxonomic identity to the phytolith producer. Additionally, with rare exceptions (e.g. Prasad et al. 2005) lagerstätten that preserve exceptional anatomical detail in fossils—and might therefore be expected to preserve silica bodies—tend to be oversaturated with respect to silica (e.g. Kidston & Lang 1920) or extremely undersaturated with respect to silica (e.g. Hatcher et al. 1982; Scott et al. 1996). To account for this, efforts to understand the history of silica biomineralization in terrestrial plants have taken a comparative biology approach (Epstein 1994; Raven 2003).

Silica is widely employed within plants for structural support and pathogen defense (Cooke & Leishman 2011; Ma 2002; Ma & Yamaji 2008), but remains a poorly understood aspect of plant biology. Recent work on the angiosperm *Oryza sativa* demonstrated that silica accumulation is facilitated by transmembrane proteins expressed in root cells (Ma 2006; Ma & Yamaji 2008; Mitani & Ma 2005; Mitani et al. 2008). Phylogenetic analysis revealed that these silicon transport proteins were derived from a diverse family of modified aquaporins that include arsenite and glycerol transporters (Cooke & Leishman 2011; Liu & Zhu 2010; Ma & Yamaji 2008; Ma et al. 2008). A different member of this aquaporin family was recently identified that enables silica uptake in the horsetail *Equisetum*—an early-diverging fern known to accumulate substantial amounts of silica (Gregoire et al. 2012). However, despite a growing number of fully sequenced genomes, angiosperm-type silicon transporters are not found within the gymnosperms or in spore-bearing plants (Anderberg et al. 2012; Liu & Zhu 2010), including plant lineages that are known to contain many weight-percent silica (Figure 1**)**. A more complete understanding of the distribution and mechanisms of silica accumulation within these early-diverging lineages is a necessary precondition for assessing the evolutionary history of silica biomineralization in terrestrial plants.

Figure 1: Stratigraphic ranges and evolutionary relationships between major terrestrial plant lineages. Although the angiosperm macrofossil record only extends to the Early Cretaceous Period (Sun et al. 2002), a strict interpretation of their position as sister group to all other seed plant clades implies an earlier origin, shown here with a dashed line (Frohlich & Chase 2007; Mathews 2009). For the purposes of this paper, we define Araucarian-type conifers as Araucariaceae and extinct relatives, and Podocarpus-type conifers as Podocarpaceae and extinct relatives. Filled stars mark clades that accumulate > 1 wt.% silica (dry matter), color coded for identified and unidentified silicon transport proteins. Stratigraphic ranges: (Taylor et al. 2008). Evolutionary relationships: (Doyle 2006; Mathews 2009; Qiu et al. 2006).



Methods

Bulk plant silica analysis using dry ashing:

Samples were collected in and around Southern California. Source locations include: Caltech grounds; The Huntington Library, Art Collections, and Botanical Gardens; and Rancho Santa Ana Botanic Garden, the private collection of Loran M. Whitelock, and commercial sources. Plant material (~ 1 g wet weight leaf, sporophyte, or photosynthetic surface sample) was rinsed and dried, and then combusted at 500˚C (Parr et al. 2001). The sample ashes were subsequently washed in 10% HCl at 70˚C, incubated again in 15% H_2O_2 at 70˚C, and dehydrated in ethanol. Final SiO_2 masses are presented as percent initial sample dry weight. Typical uncertainty of the dry ashing method is less than 0.1 wt.% SiO_2 (Ali et al. 1988; Jorhem 1995)—much smaller than the natural variation between tissues of a single plant (e.g. Carnelli et al. 2001). Previously published silica abundance data whose primary sources could be verified (e.g. Hodson et al. 2005) were combined with our results. The complete list of all silica abundances are reported as SiO_2 wt.% in **Supplementary Table S1**.

Imaging and elemental mapping of silica bodies:

A representative subset of washed ash powders was selected for imaging and elemental analysis via electron microscopy and energy dispersive spectroscopy. Samples were pressed gently on to a carbon tape coated SEM stub and either carbon or palladium sputter-coated then imaged with a Zeiss 1550 VP Field Emission Scanning Electron Microscope to observe microstructures. Chemistry was also confirmed by creating spectral element maps with an Oxford INCA Energy 300 X-ray Energy Dispersive Spectrometer system.

NIP phylogeny and structure prediction:

Sequences were collected from the NCBI nr/nt database using the NIP homolog XP_002986711.1 as a query. 1000 sequences were retrieved and aligned and manipulated with Jalview (Waterhouse et al. 2009) and CLUSTALO (Sievers et al. 2011) with a full distance matrix for each iteration and 10 iterations. The alignment was manually trimmed to obtain an alignment block, and a tree constructed with Fasttree (Price et al. 2010). This first tree was used to identify the NIP group. NIP sequences were then collected along with three closely related bacterial homologs, leaving 686 unique NIP protein sequences. These were then re-aligned with CLUSTALW(Larkin et al. 2007) using default gap extension and opening penalties, and the Gonnet substitution matrix. Prottest (Darriba et al. 2011) was then used to identify an appropriate evolutionary model for tree construction. Fasttree was again used to construct a tree, and this tree was then used as a starting tree for optimization by PhyML (Guindon et al. 2010). The tree was constructed with JTT+I+G, 8 rate substitution categories, the best of NNI's and SPR's, and aBayes was used to evaluate branch supports. From this phylogeny of NIP proteins, each lineage (I, II, and III) was analyzed for sequence conservation using WebLogo3 (Crooks et al. 2004). Residues in the NIP Ar/R filter region were then selected to display diversity at these positions. A representative subset of NIPI,II,III sequences was selected for structure prediction to visualize pore geometries. Models of NIP homologs were generated through sequence submission to the iterative threading assembly refinement (I-TASSER) server (Roy et al. 2010; Zhang 2008; Zhang 2009). The top model based on C-score was selected for further analysis (Wu & Zhang 2007). One of each NIP type was analyzed using PoreWalker (Pellegrini-Calace et al. 2009) to identify pore-lining residues from the modeled structures and observe constriction at the Ar/R gate. All structures were visualized using PyMol. Whole sequence alignments for each of the protein classes, and the phylogenetic trees used in this study can be found in the *Supplementary Material* of the online version of (Trembath-Reichert et al. 2015).

Results and Discussion

We measured SiO_2 content within and across a diverse set of terrestrial plants (88 different plants from 23 families) collected in Southern California, with a focus on lesser-studied lineages with long fossil records. Silica content was assessed gravimetrically on bulk above-ground plant tissues using a modified dry ashing technique, and the resulting silica bodies were imaged using scanning electron microscopy and microscale energy dispersive spectroscopy (see *Methods*). We combined these results with previously published observations (Hodson et al. 2005; Ma 2002; Ma 2006; Ma & Yamaji 2008) to build a coherent picture of silica biomineralization in land plants (Figure 2).

The observed pattern of silica abundance among extant plants (Figure 1, Figure 2) implies a protracted evolutionary history of silica biomineralization and indicates many plant groups with long fossil records precipitate substantial amounts of silica. Accumulation of silica is widespread among diverse land plant families, and variance within groups is also high. Consistent with previous work, plants with high silica concentrations include members of the monocots, specifically grasses and sedges (Hodson et al. 2005; Ma 2002). However, we also observed that many members of early diverging lineages (e.g., Sellaginellacae, Equisetaceae, Marattiacaeae, and Osmundaceae; toward the left of Figure 2) contain as much or greater amounts of silica than the grasses and sedges (Ma 2002). The only groups that show consistently low silica abundances are found in the gymnosperms, including the conifers, ginkgo, and many cycads. Exceptions are *Gnetum gnemon* and *Cycas revoluta*, which have greater than 1 percent dry weight silica. Beyond gnetophytes and cycads, however, there is a general paucity of silica in gymnosperms suggesting this form of biomineralization is not an important feature of their biology (Carnelli et al. 2001; Hodson et al. 2005; Mitani & Ma 2005).

Additionally, the evolution of seed plants must then require either multiple gains or losses of silica biomineralization. The hypothesis that some lineages of seed plants (Araucarian-type conifers, Podocarpus-type conifers, Pinaceae) have lost biomineralization capacity is possible (Ma 2002; Ma & Yamaji 2008), however the observation that two gnetophytes, *Gnetum* and *Ephedra,* each accumulate silica and contain silicified cell walls (Figure 2, Figure 3) complicates this scenario. This distribution of silica abundance either implies a secondary gain of biomineralization within the gnetophytes, and a loss in the last common ancestor of all gymnosperms, or several independent losses of Si-accumulation within gymnosperms. We use this hypothetical framework to evaluate evolution of the molecular mechanisms of silica accumulation in terrestrial plants.

The most well characterized means by which plants accumulate silicic acid from soil water is via transmembrane proteins with selective pores that belong to a plant-specific subfamily of the aquaporins termed nodulin 26-like intrinsic proteins (NIPs) (see refs: Abascal et al. 2014; Johanson & Gustavsson 2002; Liu & Zhu 2010; Zardoya 2005). Our observations from electron microscopy and spectroscopy confirmed the presence of silicified cell wall structures in diverse taxa, including *Equisetum*, *Selaginella*, and *Gnetum* species (Figure 3**)**. Where we can resolve anatomical structures in the SiO_2 residues, the most heavily biomineralized structures are parts of the vascular system, epidermal cells, and stomata. This is consistent with the hypothesis of a transpiration driven transport process in these plant groups, in which silicic acid is assimilated by roots and is subsequently deposited as silica bodies throughout the plant via distillation (Ma & Yamaji 2008; Mitani & Ma 2005).

Figure 2: Violin plots of silica abundance in terrestrial plant families. Kernel density estimates, green fill (n=688) of silica abundance across terrestrial plant families. White dots are medians, top and bottom of the thick bar mark 1st and 3rd quartile ranges, respectively. Following the family name in parentheses is the number of total analyses within that group, followed by the number of analyses in that group from this study. Families are arranged from left to right in rough order of evolutionary divergence. For clarity, we did not display data from several angiosperm families that are not known to accumulate silica (see *Supplementary Methods*). Conifers and more recently diverging fern clades (e.g., Polypodiaceae) have the lowest medians, whereas liverworts, mosses, lycophytes, and eusporangiate ferns have higher weight percent silica (dry matter), with median values that approach or exceed those found in grasses (Poaceae) and sedges (Cyperaceae).

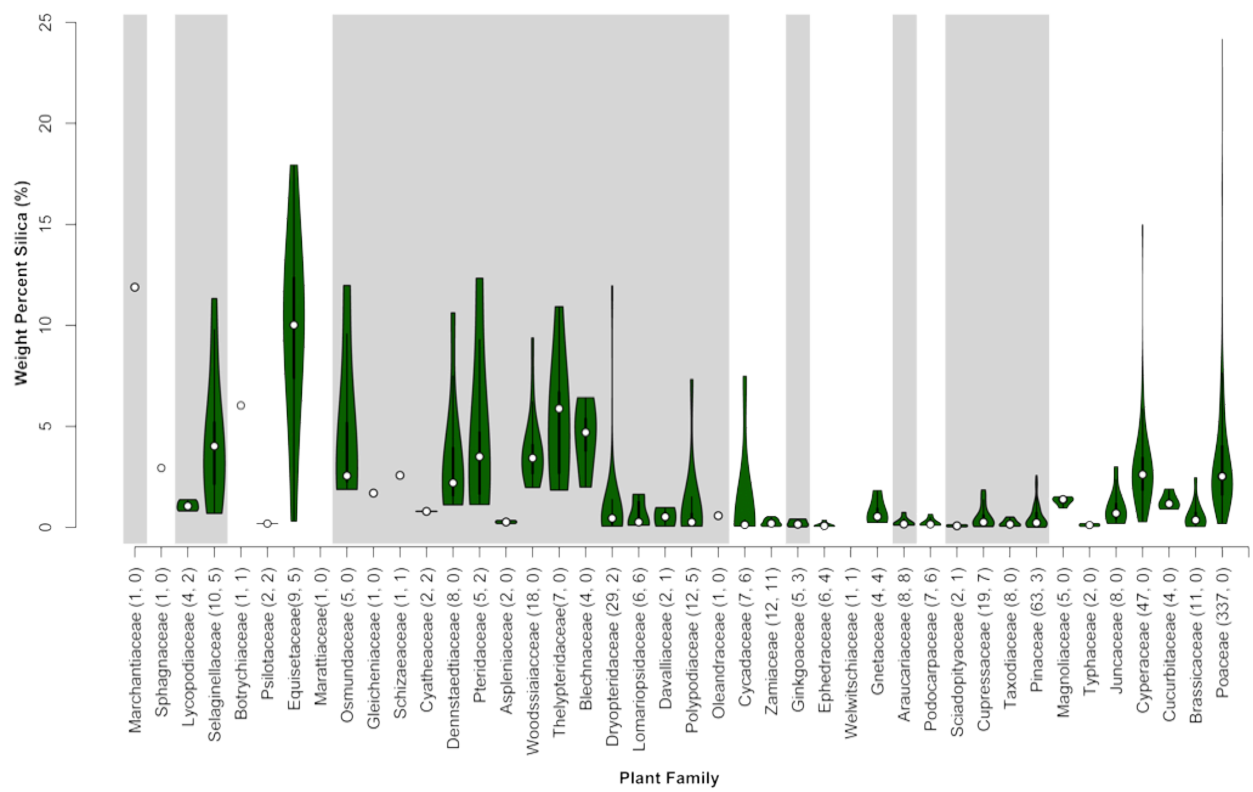
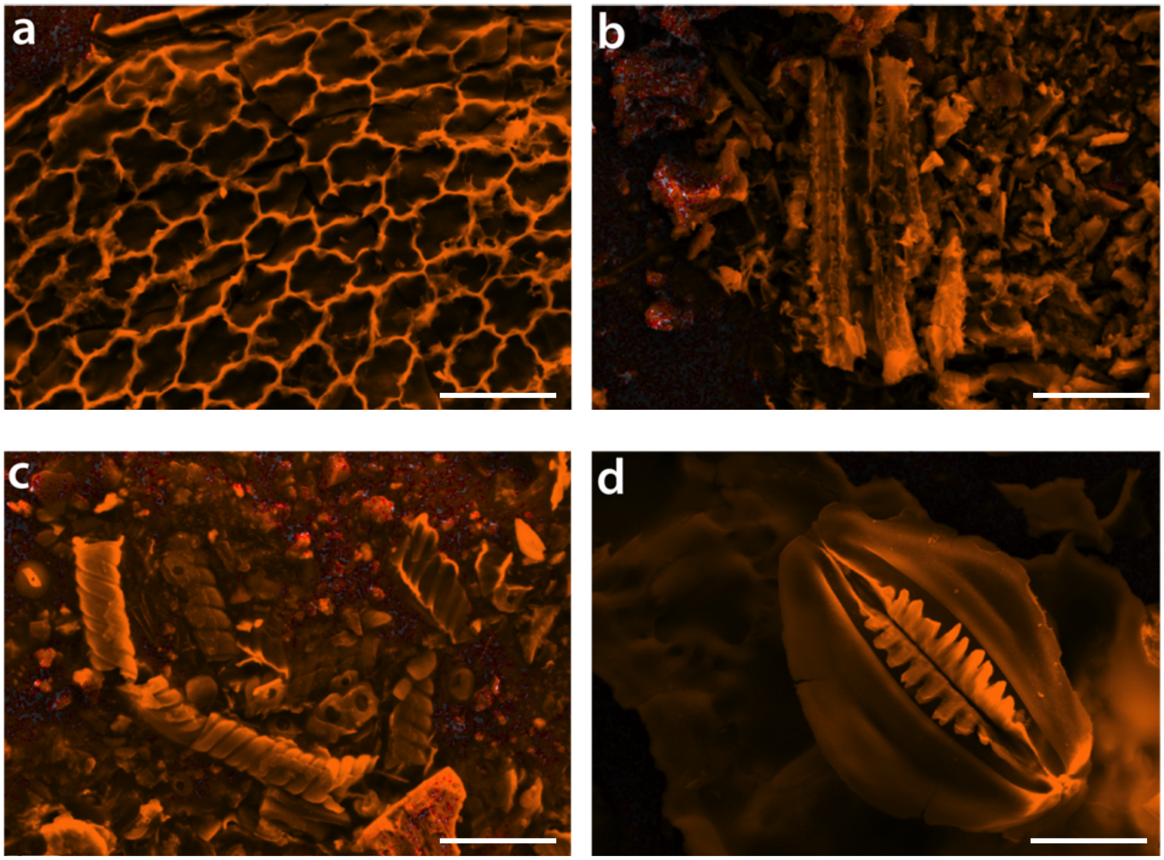


Figure 3: Secondary electron images of silica bodies (grayscale) overlaid with Si maps from energy-dispersive X-ray spectroscopy (orange). Scale bar in all images is 25 μm. a) *Selaginella sp.*, b) *Gnetum gnemon*, c) *Ephedra californicum*, and d) *Equisetum hyemale*. Some distinct mineralized plant tissues can be recognized: in a, epidermal cell walls are silicified; in c, possible silicified vascular tissue; and in d, a silicified stomatal complex. It is noteworthy that these tissues are all near the sites of transpiration.



The NIPs can be subdivided into three groups based on phylogenetic relationships (Zardoya 2005; Zardoya et al. 2002) (Figure 4a). Amino acid residues that surround the narrowest portion of the pore confer a selectivity filter responsible for the exclusion of larger molecules, termed the aromatic/arginine filter (Ar/R filter or gate) (Ar/R filter or gate, Fu et al. 2000; Liu & Zhu 2010). NIPI and NIPII groups are thought to be responsible for the movement of a range of solutes, including arsenite and glycerol (Wallace & Roberts 2005). Of the three major lineages of the NIP proteins, selective transport of orthosilicic acid has been demonstrated in members of the NIPIII (*Lsi1*) and the NIPII group (Figure 4a, arrows), where the presence of a relatively large aperture at the Ar/R filter is thought to permit the passage of silicic acid as compared to smaller constrictions in other NIPs that would only allow smaller solutes passage (Gregoire et al. 2012; Ma 2006; Ma & Yamaji 2008; Mitani et al. 2008; Mitani-Ueno et al. 2011).

To evaluate the distribution and evolution of silica transport biochemistry in land plants, we constructed a phylogenetic tree and built structural models of key members from all three NIP subgroups (see *Methods*). The phylogenetic analyses recover the expected salient relationships between the NIP subgroups with ~25 times more sequence data then previous reports (Abascal et al. 2014; Liu & Zhu 2010; Zardoya 2005). Results show a complex pattern of functional evolution. Two of the three NIP subgroups have highly conserved residues at Ar/R gate positions (Figure 4a). NIPI is predominantly WVAR (Figure 4a, maroon). Nearly all NIPIII members display GSGR (Figure 4a, purple), with the exceptions of a CSGR bearing homolog in the Cucurbitaceae (*Cucumis melo* and *Cucumis sativus*), where silicon transporters were bred out for rind softening (Liu & Zhu 2010; Piperno et al. 2002) and also in the string bean *Phaseolus vulgaris* that has a single NIPIII homolog with ASGR, and in *Eucalyptus grandis*, which contains a homolog coding for GSPT at the Ar/R gate position. By contrast, NIPII is highly diverse (Figure 4a, orange). The earliest diverging NIPs are found in the moss *Physcomitrella patens*, the lycophyte *Selaginella moellendorffii,* and the fern *Adiantum capillus-verneris* (Figure 4a, asterisk). Sister to these are bacterial NIP-like MIPs (bNIPs, Danielson & Johanson 2010) represented here by sequences from *Ktedonobacter racemifer* and *Nitrolancea hollandica*, both members of the Chloroflexi. Both these bNIPs and the early diverging plant NIPs display the Ar/R gate residues FAAR (or NNAR in the case of the *Selaginella moellendorffii* homolog XP_002986711.1). Proteins with this motif have not been studied *in vivo*, but the prevalence of FAAR residues suggests that the last common ancestor to the plant NIPs may have had conserved function. NIPIIIs form a clade derived from NIPs with the FAAR motif, and are only found in angiosperms. Based upon their conserved Ar/R filter, NIPIIIs facilitate silicic acid uptake (Liu & Zhu 2010; Ma 2008) (Figure 4). NIPIs form a diverse clade, but with conserved pore residues and presumably function as water, glycerol, and lactic acid transporters (Liu & Zhu 2010). By contrast, NIPIIs are not only diverse, but show extreme sequence diversity at the Ar/R gate. Our structural models (Figure 4b) are consistent with the hypothesis that they may transport a range of larger molecules (Liu & Zhu 2010). Included in the NIPIIs are a group of recently identified, highly efficient (twice the silicic acid conductance of *Lsi1*) silicic acid transporters with the previously unreported Ar/R gate residues STAR from the horsetail *Equisetum arvense*, demonstrating that porins facilitating silicic acid transport have evolved at least twice in plants (Gregoire et al. 2012). Notably, the model structure of the ANAR porins from *Selaginella moellendorffii* has similar size and chemistry to both the STAR porin found in *Equisetum arvense* and the NIPIIIs.

A reasonable evolutionary scenario that satisfies both biochemical and empirical silicic acid abundance data begins with the evolution of NIP-like proteins with an Ar/R conformation of FAAR in bacteria from an ancestral aquaporin, followed by horizontal gene transfer into early terrestrial plants, resulting in the FAAR NIPs found in mosses. The ancestral NIPs subsequently diversified into the NIPI and NIPII clades found throughout land plants, including the functional diversity of pore residues found in the NIPIIs—at least some of which enable selective silicic acid uptake (STAR porin). Despite many fully sequenced genomes, NIPIIs are rare in gymnosperms. It is possible that silica biomineralization was lost in the last common ancestor of seed plants, and angiosperm NIPIIIs constitute a secondary gain of function (Danielson & Johanson 2010; Liu & Zhu 2010), with gnetophyte silica biomineralization currently unresolved, awaiting further molecular data. The NIP phylogeny implies an adaptive radiation of metalloid (including silicic acid) transport early within land plants (Liu & Zhu 2010) and is consistent with our observations of silica biomineralization in early-diverging lineages (Zardoya et al. 2002).

Figure 4: Phylogeny and predicted structures of nodulin 26-like intrinsic protein (NIP) clades. a) Phylogenic tree of major NIP clades with NIP I (maroon), NIP II (orange), and NIP III (purple). The frequency of amino acid occurrence at the Ar/R filter are displayed for the NIPI, NIPII, and NIPIII groups by: Hydrophilic = RKDENQ (blue), Neutral = SGHTAP (green), Hydrophobic =YVMCLFIW (black). The maximum of each scale is 1.0, or 100% probability. Unclassified NIP groups with a conserved Ar/R residues FAAR are indicated by an asterisk. Verified silica transporters include the NIPIIIs and some members of the NIPIIs, shown here with arrows. b) Structural models of four representatives of each of the NIP subgroups. Pore-lining residues are identified with Porewalker. Residues of the Ar/R filter are colored by hydrophobicity on a green scale. A longitudinal transmembrane view of three *Orzya sativa* representatives of the NIPs (I, II, III) is depicted at the top of each panel. Below is the same pore as above with three additional ribbon diagrams rotated to show a transverse view of the pore and four Ar/R gate residues.

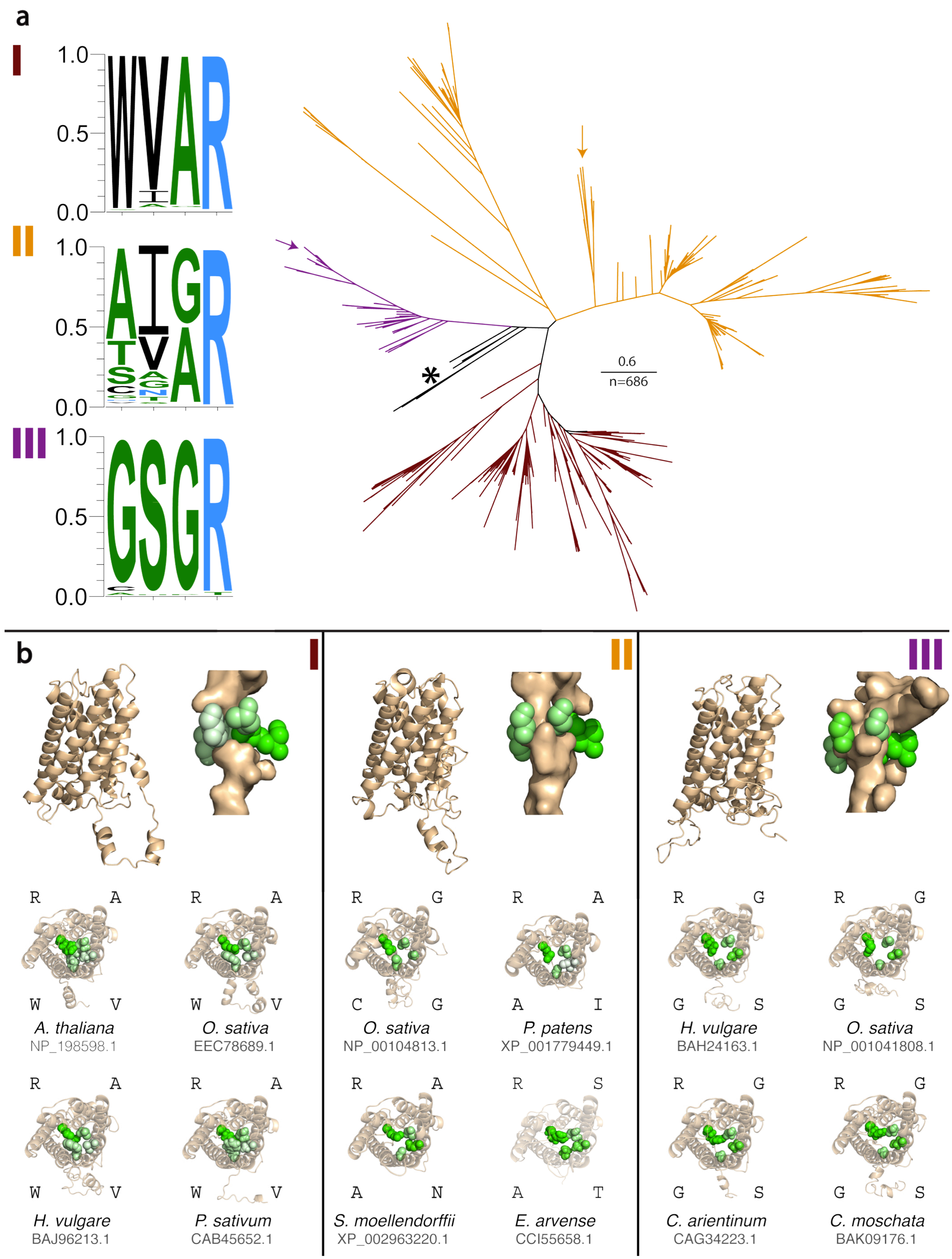
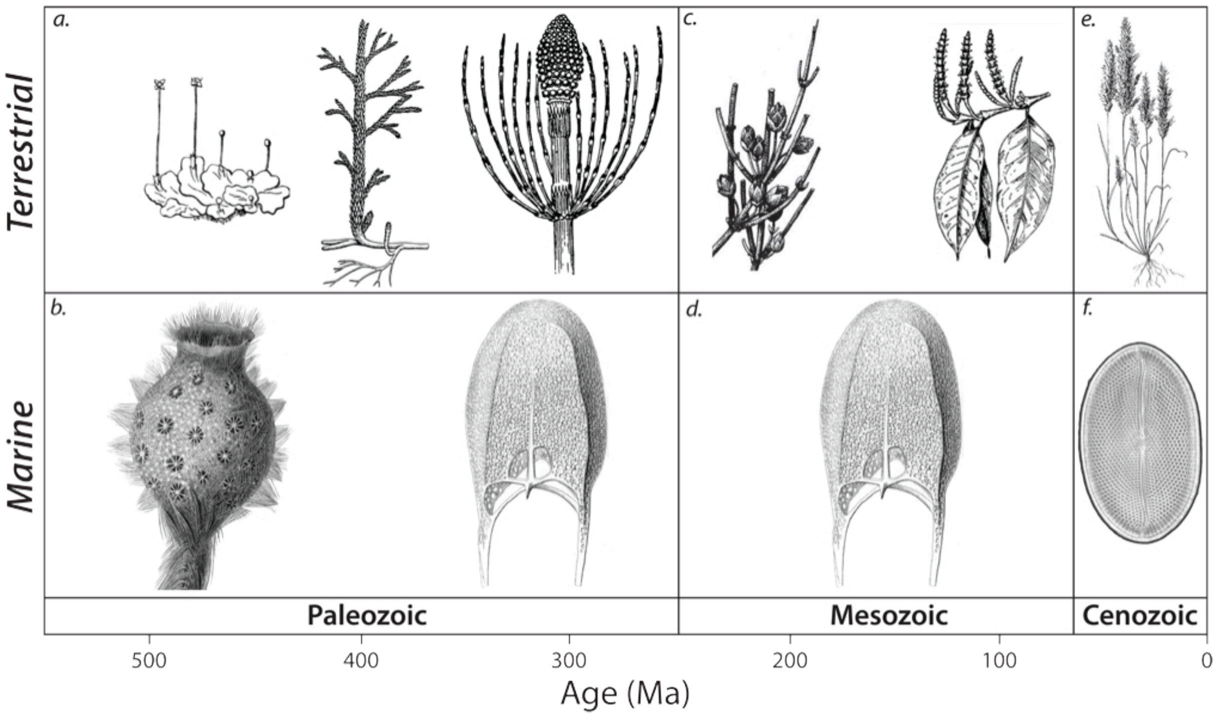

a
I
II
III
1.0
0.5
0.0
0.6
n=686
b
A. thaliana
NP_198598.1
O. sativa
EEC78689.1
H. vulgare
BAJ96213.1
P. sativum
CAB45652.1
O. sativa
NP_00104813.1
P. patens
XP_001779449.1
S. moellendorffii
XP_002963220.1
E. arvense
CCI55658.1
H. vulgare
BAH24163.1
O. sativa
NP_001041808.1
C. arientinum
CAG34223.1
C. moschata
BAK09176.1

Figure 5: Major players in the silica cycle over Phanerozoic time. a) Early-evolving nonvascular and vascular plants, including liverworts, lycophytes, and horsetails. b) Radiolaria and siliceous sponges. c) Seed plants including *Ephedra* and *Gnetum*. d) Mesozoic radiolaria lineages. e) Grasses. f) Diatoms. Fluctuating diversity and abundance of these different taxonomic groups through time, combined with uneven concentration of silica in different plant organs, suggests that plants have played a major, and dynamic, role in the silica cycle over the last 400 million years.



Summary

In order of appearance, major players in the terrestrial silica cycle include some bryophytes (liverworts), lycophytes, and early-diverging vascular plants (horsetails, eusporangiate ferns), followed by gnetophytes and grasses. Terrestrial plant lineages with roots in the Paleozoic Era, including lycophytes, horsetails, and ferns, accumulate silica at abundances comparable to or exceeding many siliceous angiosperm lineages. Combining our results with stratigraphic ranges of silica-biomineralizing plants from the fossil record, we hypothesize that a terrestrial silica cycle must have developed no later than the time of the Rhynie Chert, which contains fossilized stem group bryophytes and vascular plants (411-407 Ma, early Devonian Period; (Kidston & Lang 1920; Mark et al. 2011; Taylor et al. 2008). Consequently, plants may have had a significant impact on the terrestrial silica cycle throughout the Middle and Late Paleozoic Era, with much of the fluxes cycled through lycophytes, horsetails, and early-diverging lineages of ferns that dominated terrestrial ecosystems at this time (Figure 5). A decrease in continental accumulation of silica may have followed throughout the Mesosoic Era as a consequence of the radiation of conifers, perhaps with some modest silica accumulation in gnetophytes and cycads. Finally, large-scale changes in the terrestrial silica cycle likely occurred with the rise of grasslands late in the Cenozoic Era (Derry et al. 2005; Stromberg 2004; Stromberg 2005; Stromberg & Feranec 2004).

Acknowledgements

The authors thank George Rossman and Victoria Orphan for laboratory equipment, Chi Ma for assistance with electron microscopy and spectroscopy, Sean Lahmeyer (The Huntington Library, Art Collections, and Botanical Gardens), Loran M. Whitelock (Eagle Rock, CA) and Lucinda McDade (Rancho Santa Ana Botanic Garden) for aid in sample collection. This project was partially supported by an O K Earl Postdoctoral Scholarship (Caltech) and a San Andreas Visiting Fellowship to The Huntington Library, Art Collections, and Botanical Gardens to J.P.W. S.E.M. was partially supported by the Agouron Institute as a Geobiology Fellow, and W.W.F. acknowledges support from the Agouron Institute.

References

Abascal F, Irisarri I, and Zardoya R. 2014. Diversity and evolution of membrane intrinsic proteins. *Biochimica et Biophysica Acta (BBA) - General Subjects* 1840:1468-1481. http://dx.doi.org/10.1016/j.bbagen.2013.12.001

Ali MW, Zoltai SC, and Radford FG. 1988. A COMPARISON OF DRY AND WET ASHING METHODS FOR THE ELEMENTAL ANALYSIS OF PEAT. *Canadian Journal of Soil Science* 68:443-447. 10.4141/cjss88-041

Anderberg HI, Kjellbom P, and Johanson U. 2012. Annotation of Selaginella moellendorffii major intrinsic proteins and the evolution of the protein family in terrestrial plants. *Frontiers in Plant Science* 3. 10.3389/fpls.2012.00033

Carey JC, and Fulweiler RW. 2012. The Terrestrial Silica Pump. *Plos One* 7:e52932. 10.1371/journal.pone.0052932

Carnelli AL, Madella M, and Theurillat J-P. 2001. Biogenic Silica Production in Selected Alpine Plant Species and Plant Communities. *Annals of botany* 87:425-434. 10.1006/anbo.2000.1355

Conley DJ. 2002. Terrestrial ecosystems and the global biogeochemical silica cycle. *Global Biogeochemical Cycles* 16:68.

Cooke J, and Leishman MR. 2011. Is plant ecology more siliceous than we realise? *Trends in Plant Science* 16:61-68. 10.1016/j.tplants.2010.10.003

Crooks GE, Hon G, Chandonia JM, and Brenner SE. 2004. WebLogo: A sequence logo generator. *Genome Research* 14:1188-1190. 10.1101/gr.849004

Danielson JAH, and Johanson U. 2010. Phylogeny of Major Intrinsic Proteins. In: Jahn TP, and Bienert GP, eds. *MIPs and Their Role in the Exchange of Metalloids*: Landes Bioscience and Springer Science+Business Media, 19-29.

Darriba D, Taboada GL, Doallo R, and Posada D. 2011. ProtTest 3: fast selection of best-fit models of protein evolution. *Bioinformatics* 27:1164-1165. 10.1093/bioinformatics/btr088

Derry LA, Kurtz AC, Ziegler K, and Chadwick OA. 2005. Biological control of terrestrial silica cycling and export fluxes to watersheds. *Nature* 433:728-731.

Doyle JA. 2006. Seed ferns and the origin of angiosperms. *The Journal of the Torrey Botanical Society* 133:169-209. 10.3159/1095-5674(2006)133[169:sfatoo]2.0.co;2

Edwards EJ, Osborne CP, Stromberg CAE, Smith SA, Bond WJ, Christin PA, Cousins AB, Duvall MR, Fox DL, Freckleton RP, Ghannoum O, Hartwell J, Huang YS, Janis CM, Keeley JE, Kellogg EA, Knapp AK, Leakey ADB, Nelson DM, Saarela JM, Sage RF, Sala OE, Salamin N, Still CJ, Tipple B, and Consortium CG. 2010. The Origins of C-4 Grasslands: Integrating Evolutionary and Ecosystem Science. *Science* 328:587-591. 10.1126/science.1177216

Epstein E. 1994. The anomaly of silicon in plant biology. *Proceedings of the National Academy of Sciences* 91:11-17.

Falkowski PG, Katz ME, Knoll AH, Quigg A, Raven JA, Schofield O, and Taylor FJR. 2004. The evolution of modern eukaryotic phytoplankton. *Science* 305:354-360. 10.1126/science.1095964

Frings P, Clymans W, Jeppesen E, Lauridsen T, Struyf E, and Conley D. 2014. Lack of steady-state in the global biogeochemical Si cycle: emerging evidence from lake Si sequestration. *Biogeochemistry* 117:255-277. 10.1007/s10533-013-9944-z

Frohlich MW, and Chase MW. 2007. After a dozen years of progress the origin of angiosperms is still a great mystery. *Nature* 450:1184-1189.

Fu DX, Libson A, Miercke LJW, Weitzman C, Nollert P, Krucinski J, and Stroud RM. 2000. Structure of a glycerol-conducting channel and the basis for its selectivity. *Science* 290:481-486. 10.1126/science.290.5491.481

Gregoire C, Remus-Borel W, Vivancos J, Labbe C, Belzile F, and Belanger RR. 2012. Discovery of a multigene family of aquaporin silicon transporters in the primitive plant Equisetum arvense. *Plant Journal* 72:320-330. 10.1111/j.1365-313X.2012.05082.x

Guindon S, Dufayard J-F, Lefort V, Anisimova M, Hordijk W, and Gascuel O. 2010. New Algorithms and Methods to Estimate Maximum-Likelihood Phylogenies: Assessing the Performance of PhyML 3.0. *Systematic Biology* 59:307-321. 10.1093/sysbio/syq010

Harper HE, and Knoll AH. 1975. Silica, diatoms, and Cenozoic radiolarian evolution. *Geology* 3:175-177. 10.1130/0091-7613(1975)3<175:sdacre>2.0.co;2

Hatcher PG, Lyons PC, Thompson CL, Brown FW, and Maciel GE. 1982. Organic matter in a coal ball: peat or coal? *Science* 217:831-833. 10.1126/science.217.4562.831

Hodson MJ, White PJ, Mead A, and Broadley MR. 2005. Phylogenetic variation in the silicon composition of plants. *Annals of botany* 96:1027-1046. 10.1093/aob/mci255

Johanson U, and Gustavsson S. 2002. A new subfamily of major intrinsic proteins in plants. *Molecular Biology and Evolution* 19:456-461.

Jorhem L. 1995. Dry ashing, sources of error, and performance evaluation in AAS. *Microchimica Acta* 119:211-218. 10.1007/BF01244000

Katz ME, Finkel ZV, Grzebyk D, Knoll AH, and Falkowski PG. 2004. Evolutionary trajectories and biogeochemical impacts of marine eukaryotic phytoplankton. *Annual Review of Ecology Evolution and Systematics* 35:523-556. 10.1146/annurev.ecolsys.35.112202.130137

Kidston R, and Lang WH. 1920. On Old Red Sandstone Plants showing Structure, from the Rhynie Chert Bed, Aberdeenshire Part III. Asteroxlon mackiei, Kidston and Lang. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* 52:643-680.

Larkin MA, Blackshields G, Brown NP, Chenna R, McGettigan PA, McWilliam H, Valentin F, Wallace IM, Wilm A, Lopez R, Thompson JD, Gibson TJ, and Higgins DG. 2007. Clustal W and clustal X version 2.0. *Bioinformatics* 23:2947-2948. 10.1093/bioinformatics/btm404

Liu Q, and Zhu Z. 2010. Functional divergence of the NIP III subgroup proteins involved altered selective constraints and positive selection. *BMC Plant Biology* 10:256.

Ma JF. 2002. *Soil, Fertilizer, and Plant Silicon Research in Japan.*

Ma JF. 2006. A silicon transporter in rice. *Nature* 440:688-688.

Ma JF. 2008. Functions and transport of silicon in plants. *Cellular and molecular life sciences* 65:3049.

Ma JF, and Yamaji N. 2008. Functions and transport of silicon in plants. *Cellular and molecular life sciences* 65:3049-3057. 10.1007/s00018-008-7580-x

Ma JF, Yamaji N, Mitani N, Xu X-Y, Su Y-H, McGrath SP, and Zhao F-J. 2008. Transporters of arsenite in rice and their role in arsenic accumulation in rice grain. *Proceedings of the National Academy of Sciences of the United States of America* 105:9931-9935. 10.1073/pnas.0802361105

Mark DF, Rice CM, Fallick AE, Trewin NH, Lee MR, Boyce A, and Lee JKW. 2011. 40Ar/39Ar dating of hydrothermal activity, biota and gold mineralization in the Rhynie hot-spring system, Aberdeenshire, Scotland. *Geochimica et cosmochimica acta* 75:555-569.

Mathews S. 2009. Phylogenetic relationships among seed plants: Persistent questions and the limits of molecular data. *Am J Bot* 96:228-236. 10.3732/ajb.0800178

Mitani N, and Ma JF. 2005. Uptake system of silicon in different plant species. *Journal of Experimental Botany* 56:1255-1261. 10.1093/jxb/eri121

Mitani N, Yamaji N, and Ma JF. 2008. Characterization of substrate specificity of a rice silicon transporter, Lsi1. *Pflugers Archiv-European Journal of Physiology* 456:679-686. 10.1007/s00424-007-0408-y

Mitani-Ueno N, Yamaji N, Zhao F-J, and Ma JF. 2011. The aromatic/arginine selectivity filter of NIP aquaporins plays a critical role in substrate selectivity for silicon, boron, and arsenic. *Journal of Experimental Botany* 62:4391-4398. 10.1093/jxb/err158

Parr JF, Lentfer CJ, and Boyd WE. 2001. A comparative analysis of wet and dry ashing techniques for the extraction of phytoliths from plant material. *Journal of Archaeological Science* 28:875-886. 10.1006/jasc.2000.0623

Pellegrini-Calace M, Maiwald T, and Thornton JM. 2009. PoreWalker: A Novel Tool for the Identification and Characterization of Channels in Transmembrane Proteins from Their Three-Dimensional Structure. *PLoS Comput Biol* 5:e1000440. 10.1371/journal.pcbi.1000440

Philippe H, Sörhannus U, Baroin A, Perasso R, Gasse F, and Adoutte A. 1994. Comparison of molecular and paleontological data in diatoms suggests a major gap in the fossil record. *Journal of Evolutionary Biology* 7:247-265. 10.1046/j.1420-9101.1994.7020247.x

Piperno DR, Holst I, Wessel-Beaver L, and Andres TC. 2002. Evidence for the control of phytolith formation in Cucurbita fruits by the hard rind (Hr) genetic locus: Archaeological and ecological implications. *Proceedings of the National Academy of Sciences* 99:10923-10928. 10.1073/pnas.152275499

Prasad V, Stromberg CAE, Alimohammadian H, and Sahni A. 2005. Dinosaur coprolites and the early evolution of grasses and grazers. *Science* 310:1177-1180. 10.1126/science.1118806

Price MN, Dehal PS, and Arkin AP. 2010. FastTree 2-Approximately Maximum-Likelihood Trees for Large Alignments. *Plos One* 5. 10.1371/journal.pone.0009490

Qiu Y-L, Li L, Wang B, Chen Z, Knoop V, Groth-Malonek M, Dombrovska O, Lee J, Kent L, Rest J, Estabrook GF, Hendry TA, Taylor DW, Testa CM, Ambros M, Crandall-Stotler B, Duff RJ, Stech M, Frey W, Quandt D, and Davis CC. 2006. The deepest divergences in land plants inferred from phylogenomic evidence. *Proceedings of the National Academy of Sciences* 103:15511-15516. 10.1073/pnas.0603335103

Raven JA. 1983. THE TRANSPORT AND FUNCTION OF SILICON IN PLANTS. *Biological Reviews* 58:179-207. 10.1111/j.1469-185X.1983.tb00385.x

Raven JA. 2003. Cycling silicon – the role of accumulation in plants. *New Phytologist* 158:419-421. 10.1046/j.1469-8137.2003.00778.x

Roy A, Kucukural A, and Zhang Y. 2010. I-TASSER: a unified platform for automated protein structure and function prediction. *Nature Protocols* 5:725-738. 10.1038/nprot.2010.5

Scott AC, Mattey DP, and Howard R. 1996. New data on the formation of Carboniferous coal balls. *Review of Palaeobotany and Palynology* 93:317-331. http://dx.doi.org/10.1016/0034-6667(95)00132-8

Sievers F, Wilm A, Dineen D, Gibson TJ, Karplus K, Li W, Lopez R, McWilliam H, Remmert M, Soeding J, Thompson JD, and Higgins DG. 2011. Fast, scalable generation of high-quality protein multiple sequence alignments using Clustal Omega. *Molecular Systems Biology* 7. 10.1038/msb.2011.75

Stromberg CAE. 2004. Using phytolith assemblages to reconstruct the origin and spread of grass-dominated habitats in the great plains of North America during the late Eocene to early Miocene. *Palaeogeography Palaeoclimatology Palaeoecology* 207:239-275. 10.1016/j.palaeo.2003.09.028

Stromberg CAE. 2005. Decoupled taxonomic radiation and ecological expansion of open-habitat grasses in the Cenozoic of North America. *Proceedings of the National Academy of Sciences of the United States of America* 102:11980-11984. 10.1073/pnas.0505700102

Stromberg CAE, and Feranec RS. 2004. The evolution of grass-dominated ecosystems during the late Cenozoic. *Palaeogeography Palaeoclimatology Palaeoecology* 207:199-201. 10.1016/j.palaeo.2004.01.017

Sun G, Ji Q, Dilcher DL, Zheng S, Nixon KC, and Wang X. 2002. Archaefructaceae, a new basal angiosperm family. *Science* 296:899-904. 10.1126/science.1069439

Taylor TN, Taylor EL, and Krings M. 2008. *Paleobotany: The Biology and Evolution of Fossil Plants*: Academic Press.

Trembath-Reichert E, Wilson JP, McGlynn SE, and Fischer WW. 2015. Four hundred million years of silica biomineralization in land plants. *Proceedings of the National Academy of Sciences of the United States of America* 112:5449-5454. 10.1073/pnas.1500289112

Wallace IS, and Roberts DM. 2005. Distinct Transport Selectivity of Two Structural Subclasses of the Nodulin-like Intrinsic Protein Family of Plant Aquaglyceroporin Channels†. *Biochemistry* 44:16826-16834. 10.1021/bi0511888

Waterhouse AM, Procter JB, Martin DMA, Clamp M, and Barton GJ. 2009. Jalview Version 2-a multiple sequence alignment editor and analysis workbench. *Bioinformatics* 25:1189-1191. 10.1093/bioinformatics/btp033

Wu S, and Zhang Y. 2007. LOMETS: A local meta-threading-server for protein structure prediction. *Nucleic Acids Research* 35:3375-3382. 10.1093/nar/gkm251

Zardoya R. 2005. Phylogeny and evolution of the major intrinsic protein family. *Biology of the Cell* 97:397-414. 10.1042/bc20040134

Zardoya R, Ding XD, Kitagawa Y, and Chrispeels MJ. 2002. Origin of plant glycerol transporters by horizontal gene transfer and functional recruitment. *Proceedings of the National Academy of Sciences of the United States of America* 99:14893-14896. 10.1073/pnas.192573799

Zhang Y. 2008. I-TASSER server for protein 3D structure prediction. *Bmc Bioinformatics* 9. 10.1186/1471-2105-9-40

Zhang Y. 2009. I-TASSER: Fully automated protein structure prediction in CASP8. *Proteins-Structure Function and Bioinformatics* 77:100-113. 10.1002/prot.22588

Supplemental Table 1: Silica abundance data for all samples from this study combined with those from previous work, organized by species Name, Order, Family, Silica (wt. %), Reference, and collection Location. Full reference information for previous studies can be found in Appendix of Hodson et al. 2005.

Name	**Silica (wt. %)**	**Reference**	**Location**
Abies alba	0.08	Carnelli et al. (2001)	
Abies balsamea	0.18	Klein & Geis (1978)	
Abies fraseri	0.13	Klein & Geis (1978)	
Abies grandis	0.84	Hodson et al. (1997)	
Abies mariesii	0.12	Hodson et al. (1997)	
Abies nordmann	0.06	This Study	Huntington
Abies nordmann	0.10	This Study	Huntington

Abies nordmanniana	0.39	Hodson et al. (1997)	
Abies pectinata	11.34	Bartoli & Beaucire (1976)	
Abies pectinata	13.37	Bartoli & Beaucire (1976)	
Abies procera	0.93	Hodson et al. (1997)	
Acer ginnala	1.13	Ma & Takahashi (2002)	
Acer negundo	0.34	Geis (1973)	
Acer rubrum	1.49	Lanning & Eleuterius (1983)	
Acer saccharinum	0.98	Geis (1973)	
Acer saccharum	2.63	Geis (1973)	
Acer saccharum	1.84	Ma & Takahashi (2002)	
Achillea millefolium	4.20	Hogenbirk & Sarrazin-Delay (1995)	
Achnatherum hymenoides	2.00	Blank *et al.* (1994)	
Achnatherum hymenoides	4.00	Blank *et al.* (1994)	
Aconitum japonicum	0.75	Ma & Takahashi (2002)	
Aconitum loczyanum	0.68	Ma & Takahashi (2002)	
Acorus calamus	0.09	Ma (2002)	
Acorus gramineus	0.21	Ma (2002)	
Acrophorus stipellatus	2.42	Ma & Takahashi (2002)	
Adiantum pedatum	1.13	Ma & Takahashi (2002)	
Adiantum pedatum	4.71	Ma & Takahashi (2002)	
Aegilops squarrosa	4.51	Ma & Takahashi (2002)	
Aesculus pavia	0.30	Lanning & Eleuterius (1983)	
Agathis robusta	0.11	This Study	Huntington
Agathis robusta	0.17	This Study	Huntington
Agave americana	0.30	Ma & Takahashi (2002)	
Agropyron cristatum	1.85	Bezeau et al. (1996)	
Agropyron dasystachyum	1.81	Bezeau *et al.* (1966)	
Agropyron repens	3.50	Hogenbirk & Sarrazin-Delay (1995)	
Agropyron smithii	2.20	Bezeau *et al.* (1966)	
Agropyron smithii	2.52	Bezeau et al. (1996)	
Agropyron subsecundum	2.23	Bezeau et al. (1996)	
Agropyron trichophorum	2.20	Bezeau et al. (1996)	
Agrostis alba	6.74	Butler & Hodges (1967)	

Agrostis gigantea	8.30	Hogenbirk & Sarrazin-Delay (1995)
Agrostis palustris	2.40	Barbehenn (1993)
Agrostis scabra	1.70	Hogenbirk & Sarrazin-Delay (1995)
Agrostis stolonifera	10.48	Tyler (1971)
Agrostis tenuis	2.89	Pahkala & Pihala (2000)
Agrostis tenuis	3.04	Pahkala & Pihala (2000)
Agrostis tenuis	3.06	Pahkala & Pihala (2000)
Alangium platanifolium	0.40	Nakanishi et al. (2003)
Albizia julibrissin	0.21	Ma & Takahashi (2002)
Alhagi mannifera	0.17	Cowgill (1989)
Allium fistulosum	0.36	Ma & Takahashi (2002)
Alnus viridis	0.13	Carnelli et al. (2001)
Aloë arborescens	0.34	Ma & Takahashi (2002)
Alternanthera sessilis	0.60	Cowgill (1989)
Amaranthus albus	0.14	Cowgill (1989)
Amaranthus gracilis	0.13	Cowgill (1989)
Amaranthus graecizans	0.09	Cowgill (1989)
Amaranthus retroflexus	0.43	Cowgill (1989)
Amaranthus spp.	5.00	Bilbro et al. (1991)
Amaranthus viridis	0.32	Ma & Takahashi (2002)
Ammi visnaga	0.37	Cowgill (1989)
Amorphophallus rivieri	0.09	Ma & Takahashi (2002)
Ananas comosus	0.51	Ma & Takahashi (2002)
Anaphalis margaritacea	0.70	Hogenbirk & Sarrazin-Delay (1995)
Andropogon gerardii	6.79	Geis 1978
Andropogon gerardii	2.89	Lanning & Eleuterius (1987)
Andropogon scoparius	9.25	Lanning & Eleuterius (1987)
Anemarrhena asphodeloides	0.17	Ma & Takahashi (2002)
Angiopteris lygodiifolia	3.55	Ma & Takahashi (2002)
Anthoxanthum odoratum	0.88	Cornelissen & Thompson (1997)
Anthoxanthum odoratum	1.09	Cornelissen & Thompson (1997)
Aquilegia flabellata	0.11	Ma & Takahashi (2002)
Aralia cordata	0.17	Ma & Takahashi (2002)

Araucaria araucana	0.85	Hodson *et al.* (1997)	
Araucaria sp.	0.11	This Study	Pasadena, CA
Araucaria sp.	0.15	This Study	Huntington
Araucaria sp.	0.15	This Study	Caltech
Araucaria sp.	0.17	This Study	Pasadena, CA
Araucaria sp.	0.66	This Study	Pasadena, CA
Araucaria sp.	0.74	This Study	Pasadena, CA
Arctostaphylos uva-ursi	0.04	Carnelli et al. (2001)	
Aristida stricta	2.48	Kalisz & Stone (1984)	
Armoracia rusticana	0.09	Ma & Takahashi (2002)	
Aronia melanocarpa	3.08	Kolesnikov & Gins (2001)	
Arrhenatherum elatius	1.80	Cornelissen & Thompson (1997)	
Artemisia absinthium	0.68	Ma & Takahashi (2002)	
Artemisia cana	0.33	Bezeau et al. (1996)	
Artemisia frigida	0.99	Bezeau et al. (1996)	
Artemisia gnaphalodes	0.16	Bezeau et al. (1996)	
Artemisia maritima	0.21	Ma & Takahashi (2002)	
Artemisia tridentata	1.40	Blank et al. (1994)	
Artemisia tridentata	0.60	Blank et al. (1994)	
Arundinaria gigantea	18.16	Lanning & Eleuterius (1985)	
Arundo donax	3.20	Bilbro et al. (1991)	
Arundo donax	2.65	Ma & Takahashi (2002)	
Asparagus cochinchinensis	0.53	Ma & Takahashi (2002)	
Asparagus officinalis	1.65	Kolesnikov & Gins (2001)	
Asparagus officinalis	0.58	Ma & Takahashi (2002)	
Aspidistra elatior	0.13	Ma & Takahashi (2002)	
Asplenium cuneifolium	0.34	Höhne & Richter (1981)	
Asplenium trichomanes	0.19	Ma & Takahashi (2002)	
Aster laevis	0.45	Bezeau et al. (1996)	
Aster macrophyllus	2.60	Hogenbirk & Sarrazin-Delay (1995)	
Aster tenuifolia	0.03	Lanning & Eleuterius (1983)	
Aster tenuifolia	0.09	Lanning & Eleuterius (1983)	
Aster tripolium	0.24	de Bakker et al. (1999)	

Athyrium filix-femina	4.09	Höhne (1963)
Athyrium filix-femina	2.80	Höhne (1963)
Athyrium filix-femina	1.97	Höhne (1963)
Athyrium filix-femina	3.47	Höhne (1963)
Athyrium filix-femina	2.33	Höhne (1963)
Athyrium filix-femina	2.46	Höhne & Richter (1981)
Athyrium filix-femina	3.38	Höhne & Richter (1981)
Athyrium japonicum	2.61	Ma & Takahashi (2002)
Athyrium lobato-crenatum	4.09	Ma & Takahashi (2002)
Athyrium niponicum	2.08	Ma & Takahashi (2002)
Athyrium yokoscense	3.06	Ma & Takahashi (2002)
Atriplex canescens	0.20	Bilbro et al. (1991)
Atriplex littoralis	0.00	de Bakker et al. (1999)
Atriplex nuttallii	0.60	Bezeau et al. (1996)
Atriplex portulacoides	0.32	de Bakker et al. (1999)
Atriplex prostrata	0.00	de Bakker et al. (1999)
Atriplex rosea	0.29	Cowgill (1989)
Atropa belladonna	0.06	Ma & Takahashi (2002)
Aucuba japonica	1.24	Ma & Takahashi (2002)
Aucuba japonica	0.53	Nakanishi et al. (2003)
Avena sativa	2.72	Bertrand & Ghitescu (1934)
Avena sativa	0.58	Grosse-Brauckmann (1953)
Avena sativa	2.03	Grosse-Brauckmann (1953)
Avena sativa	2.04	Jones & Handreck (1967)
Avena sativa	4.45	Ma & Takahashi (2002)
Avena sativa	2.90	McManus et al. (1977)
Avena sativa	3.68	Saijonkari-Pahkala (2001)
Avena sativa	5.13	Schnug & v. Franck (1985)
Avena sativa	8.56	Schnug & v. Franck (1985)
Avena sativa	17.12	Schnug & v. Franck (1985)
Baccharis halimifolia	0.28	Ma & Takahashi (2002)
Baccharis trimera	0.82	Pereira & Felcman (1998)
Bacopa monnieri	1.18	Lanning & Eleuterius (1983)

Ballota undulata	0.40	Cowgill (1989)	
Batis maritima	0.27	Lanning & Eleuterius (1985)	
Benincasa hispida	0.90	Ma & Takahashi (2002)	
Betonica foliosa	2.44	Kolesnikov & Gins (2001)	
Betula pendula	0.83	Bartoli & Beaucire (1976)	
Blechnum amabile	1.99	Ma & Takahashi (2002)	
Blechnum spicant	6.42	Höhne & Richter (1981)	
Blechnum spicant	4.36	Höhne & Richter (1981)	
Bletilla striata	1.01	Ma & Takahashi (2002)	
Boltonia asteroides	2.00	Lanning & Eleuterius (1983)	
Borrichia frutescens	0.38	Lanning & Eleuterius (1983)	
Borrichia frutescens	0.39	Lanning & Eleuterius (1985)	
Botrychium virginianum	6.04	This Study	Commercial
Bouteloua curtipendula	5.64	Smith et al. (1971)	
Bouteloua gracilis	2.17	Bezeau et al. (1996)	
Bouteloua gracilis	2.51	Johnston et al. (1967)	
Bouteloua gracilis	2.45	Johnston et al. (1967)	
Bouteloua gracilis	2.60	Johnston et al. (1967)	
Bouteloua gracilis	3.24	Johnston et al. (1967)	
Bouteloua gracilis	1.30	Johnston et al. (1967)	
Bouteloua gracilis	2.26	Johnston et al. (1967)	
Bouteloua gracilis	2.51	Johnston et al. (1967)	
Bouteloua gracilis	2.12	Johnston et al. (1967)	
Bouteloua gracilis	1.77	Johnston et al. (1967)	
Bouteloua gracilis	2.73	Johnston et al. (1967)	
Bouteloua gracilis	5.72	Smith et al. (1971)	
Bouteloua hirsuta	6.68	Smith et al. (1971)	
Brachypodium pinnatum	1.97	Cornelissen & Thompson (1997)	
Brachypodium sylvaticum	6.50	Höhne (1963)	
Brachypodium sylvaticum	5.56	Höhne (1963)	
Brachypodium sylvaticum	8.41	Höhne (1963)	
Brachypodium sylvaticum	5.71	Höhne (1963)	
Brassica alba	0.15	Jones & Handreck (1967)	

Brassica napus	0.03	Bertrand & Ghitescu (1934)
Brassica napus	0.36	Saijonkari-Pahkala (2001)
Brassica rapa	0.14	Saijonkari-Pahkala (2001)
Brassica rapa	0.43	Schnug & v. Franck (1985)
Brassica rapa	1.07	Schnug & v. Franck (1985)
Brassica rapa	1.07	Schnug & v. Franck (1985)
Briza media	1.80	Cornelissen & Thompson (1997)
Bromus inermis	2.47	Bezeau et al. (1996)
Bromus inermis	4.30	Hogenbirk & Sarrazin-Delay (1995)
Bromus inermis	1.30	Robbins et al. (1987)
Bromus pumpellianus	1.86	Bezeau et al. (1996)
Bromus tectorum	1.50	Blank et al. (1994)
Bromus tectorum	3.40	Blank et al. (1994)
Bromus tectorum	2.40	Robbins et al. (1987)
Cajanus cajan	2.80	Bilbro et al. (1991)
Calamagrostis canadensis	4.90	Hogenbirk & Sarrazin-Delay (1995)
Calamagrostis epigejos	4.58	Höhne (1963)
Calamagrostis epigejos	6.33	Höhne (1963)
Calamagrostis epigejos	4.02	Höhne (1963)
Calamagrostis epigejos	4.17	Höhne (1963)
Calamagrostis inexpansa	3.80	Bezeau et al. (1996)
Calamagrostis rubescens	3.29	Bezeau et al. (1996)
Calamagrostis villosa	5.90	Carnelli et al. (2001)
Calamagrostis villosa	7.40	Höhne (1963)
Calamagrostis villosa	3.27	Höhne (1963)
Calamagrostis villosa	5.24	Höhne (1963)
Callistemon rigidus	0.19	Ma & Takahashi (2002)
Calluna vulgaris	5.35	Bartoli & Beaucire (1976)
Calluna vulgaris	0.72	Carnelli et al. (2001)
Calluna vulgaris	1.69	Höhne (1963)
Calystegia japonica	0.04	Ma & Takahashi (2002)
Calystegia sepium	0.13	Cowgill (1989)
Camellia japonica	0.13	Ma & Takahashi (2002)

Camellia japonica	0.24	Nakanishi et al. (2003)
Camellia sasanqua	0.32	Ma & Takahashi (2002)
Camellia sasanqua	0.45	Nakanishi et al. (2003)
Campsis grandiflora	0.30	Ma & Takahashi (2002)
Canna indica	0.77	Ma & Takahashi (2002)
Cannabis sativa	0.19	Saijonkari-Pahkala (2001)
Capsicum annuum	0.11	Taber et al. (2002)
Carex aquatilis	1.15	Gadallah & Jefferies (1995)
Carex atherodes	2.71	Bezeau et al. (1996)
Carex biwensis	2.61	Ma & Takahashi (2002)
Carex cinica	5.43	Ma & Takahashi (2002)
Carex curvula	1.03	Carnelli et al. (2001)
Carex dispalata	5.16	Ma & Takahashi (2002)
Carex filifolia	2.76	Bezeau et al. (1996)
Carex filifolia	1.21	Johnston et al. (1967)
Carex filifolia	3.66	Johnston et al. (1967)
Carex filifolia	2.99	Johnston et al. (1967)
Carex filifolia	3.10	Johnston et al. (1967)
Carex filifolia	1.48	Johnston et al. (1967)
Carex filifolia	3.92	Johnston et al. (1967)
Carex filifolia	2.47	Johnston et al. (1967)
Carex filifolia	2.88	Johnston et al. (1967)
Carex filifolia	2.47	Johnston et al. (1967)
Carex filifolia	3.33	Johnston et al. (1967)
Carex flacca	1.82	Cornelissen & Thompson (1997)
Carex flavicans	2.20	Gadallah & Jefferies (1995)
Carex parciflora	3.70	Ma & Takahashi (2002)
Carex sempervirens	2.31	Carnelli et al. (2001)
Carex subspathacea	2.70	Gadallah&Jefferies (1995)
Carex thunbergii	3.57	Ma & Takahashi (2002)
Carpinus caroliniana	0.62	Geis (1973)
Carya cordiformis	0.26	Geis (1973)
Carya laciniosa	0.32	Geis (1973)

Carya ovata	0.46	Geis (1973)	
Carya tomentosa	0.36	Geis (1973)	
Caryota mitis	2.76	Lanning (1966)	
Catalpa ovata	0.43	Ma & Takahashi (2002)	
Catalpa ovata	0.97	Nakanishi et al. (2003)	
Cedrus atlantica	0.09	Hodson et al. (1997)	
Celtis occidentalis	3.44	Geis (1973)	
Celtis occidentalis	8.80	Wilding & Drees (1971)	
Cenchrus longispinus	3.38	Lanning & Eleuterius (1987)	
Centaurea iberica	0.32	Cowgill (1989)	
Ceratiola ericoides	0.07	Lanning & Eleuterius (1985)	
Ceratozamia hildae	0.10	This Study	Huntington
Cercidiphyllum japonicum	2.01	Ma & Takahashi (2002)	
Cercidiphyllum japonicum	0.82	Nakanishi et al. (2003)	
Cercis canadensis	0.20	Geis (1973)	
Chaenomeles sinensis	0.62	Ma & Takahashi (2002)	
Chamaecyparis lawsoniana	1.85	Hodson et al. (1997)	
Chamaecyparis obtusa	1.09	Hodson et al. (1997)	
Chamaecyparis obtusa	0.26	Ma & Takahashi (2002)	
Chamaecyparis pisifera	0.79	Hodson et al. (1997)	
Chamaecyparis thyoides	1.38	Lanning & Eleuterius (1985)	
Chamerion angustifolium	0.13	Cornelissen & Thompson (1997)	
Chamomilla recutita	0.34	Ma & Takahashi (2002)	
Chasmanthium latifolium	7.74	Lanning & Eleuterius (1989)	
Chasmanthium sessiliflorum	0.43	Lanning & Eleuterius (1989)	
Chenopodium album	0.18	Cowgill (1989)	
Chenopodium album	0.00	Lanning & Eleuterius (1983)	
Chenopodium murale	0.36	Cowgill (1989)	
Chenopodium opulifolium	0.23	Cowgill (1989)	
Chrysanthemum coronarium	0.39	Ma & Takahashi (2002)	
Chrysanthemum morii	0.62	Reay & Bennett (1987)	
Citrullus lanatus	1.90	Taber et al. (2002)	
Cladium jamaicense	2.35	Lanning & Eleuterius (1983)	

Cladium mariscus	2.02	Cowgill (1989)	
Clethra alnifolia	1.97	Lanning & Eleuterius (1985)	
Cleyera ochnacea	0.27	Nakanishi et al. (2003)	
Cliftonia monophylla	0.30	Lanning & Eleuterius (1985)	
Coffea arabica	0.17	Lanning (1966)	
Colysis decurrens	0.64	Ma & Takahashi (2002)	
Colysis wrightii	0.06	Ma & Takahashi (2002)	
Conium maculatum	0.06	Ma & Takahashi (2002)	
Convallaria majalis	1.13	Ma & Takahashi (2002)	
Conyza canadensis	0.16	Cowgill (1989)	
Cornucopiae cucullatum	0.80	Cowgill (1989)	
Cornus stolonifera	0.20	Geis (1973)	
Cortaderia selloana	0.21	Lanning & Eleuterius (1989)	
Cortaderia selloana	1.39	Ma & Takahashi (2002)	
Corylopsis pauciflora	0.37	Nakanishi et al. (2003)	
Crataegus cuneata	0.24	Ma & Takahashi (2002)	
Crinum asiaticum	0.04	Ma & Takahashi (2002)	
Cryptomeria japonica	0.18	Hodson et al. (1997)	
Cryptomeria japonica	0.30	Ma & Takahashi (2002)	
Ctenitis subglandulosa	1.05	Ma & Takahashi (2002)	
Ctenium aromaticum	5.91	Lanning & Eleuterius (1985)	
Cunninghamia lanceolata	0.06	Hodson et al. (1997)	
Cunninghamia lanceolata	0.13	Ma & Takahashi (2002)	
Cupania oblongifolia	0.27	Pereire & Felcman (1998)	
Cupressocyparis leylandii	1.73	Hodson et al. (1997)	
Cupressus sempervirens	0.21	Ma & Takahashi (2002)	
Cuscuta planiflora	0.16	Cowgill (1989)	
Cuscuta racemosa	0.03	Pereire & Felcman (1998)	
Cyathea cooperi	0.78	This Study	Huntington
Cyathea cooperi	0.80	This Study	Huntington
Cycas revoluta	0.15	Ma & Takahashi (2002)	
Cycas revoluta	0.05	This Study	Huntington
Cycas revoluta	0.10	This Study	Huntington

Cycas revoluta	0.13	This Study	Huntington
Cycas revoluta	7.49	This Study	Huntington
Cycas revoluta (less dry)	0.08	This Study	Huntington
Cycas revoluta (less dry)	0.25	This Study	Huntington
Cyclosorus acuminatus	7.00	Ma & Takahashi (2002)	
Cyclosorus dentatus	10.93	Ma & Takahashi (2002)	
Cymbopogon citratus	1.82	Ma & Takahashi (2002)	
Cynanchum acutum	0.15	Cowgill (1989)	
Cynodon dactylon	4.47	Barbehenn (1993)	
Cynodon dactylon	7.68	Butler & Hodges (1967)	
Cynodon dactylon	3.08	Lanning (1966)	
Cynodon dactylon	2.49	Street (1974)	
Cynodon dactylon	3.85	Street (1974)	
Cynodon dactylon	0.32	Street (1974)	
Cynodon dactylon	2.49	Street (1974)	
Cynodon dactylon	3.85	Street (1974)	
Cyperus alopecuroides	0.49	Cowgill (1989)	
Cyperus alternifolius	7.53	Ma & Takahashi (2002)	
Cyperus latifolius	1.00	Cowgill (1989)	
Cyperus michelianus	1.04	Cowgill (1989)	
Cyperus microiria	1.95	Ma & Takahashi (2002)	
Cyperus papyrus	0.27	Cowgill (1989)	
Cyperus papyrus	1.20	Lanning (1966)	
Cyperus papyrus	3.74	Ma & Takahashi (2002)	
Cyperus polystachyos	1.86	Lanning & Eleuterius (1985)	
Cyperus surinamensis	2.36	Lanning & Eleuterius (1985)	
Cyrtomium falcatum	0.28	Ma & Takahashi (2002)	
Cyrtomium falcatum	0.16	This Study	Huntington
Cyrtomium falcatum	0.19	This Study	Huntington
Cyrtomium falcatum	0.59	This Study	Huntington
Cyrtomium falcatum	2.51	This Study	Huntington
Cyrtomium fortunei	0.49	Ma & Takahashi (2002)	
Dactylis glomerata	1.20	Cornelissen & Thompson (1997)	

Danthonia intermedia	3.08	Bezeau et al. (1996)	
Danthonia parryi	2.61	Bezeau et al. (1996)	
Daphne odora	0.19	Ma & Takahashi (2002)	
Daphne odora	0.24	Nakanishi et al. (2003)	
Davallia fejeensis	0.07	This Study	Huntington
Davallia mariesii	0.98	Ma & Takahashi (2002)	
Dennstaedtia scabra	4.07	Ma & Takahashi (2002)	
Deschampsia cespitosa	1.85	Bezeau et al. (1996)	
Deschampsia cespitosa	2.55	Höhne (1963)	
Deschampsia cespitosa	2.89	Höhne (1963)	
Deschampsia cespitosa	2.72	Höhne (1963)	
Deschampsia cespitosa	3.15	Höhne (1963)	
Deschampsia cespitosa	1.86	Johnston et al. (1967)	
Deschampsia cespitosa	4.53	Johnston et al. (1967)	
Deschampsia flexuosa	0.68	Cornelissen & Thompson (1997)	
Deschampsia flexuosa	0.98	Höhne (1963)	
Deschampsia flexuosa	1.41	Höhne (1963)	
Deschampsia flexuosa	1.78	Höhne (1963)	
Deschampsia flexuosa	0.51	Höhne (1963)	
Deschampsia flexuosa	0.45	Höhne (1963)	
Deschampsia flexuosa	1.95	Höhne (1963)	
Deschampsia flexuosa	1.43	Höhne (1963)	
Desmodium uncinatum	0.30	McManus et al. (1977)	
Dianthus superbus	0.13	Ma & Takahashi (2002)	
Digitaria decumbens	2.20	McManus et al. (1977)	
Digitaria ischaemum	8.09	Butler & Hodges (1967)	
Dioon spinulosum	0.06	This Study	Pasadena, CA
Diplazium hachijoense	9.39	Ma & Takahashi (2002)	
Diplazium wichurae	3.57	Ma & Takahashi (2002)	
Distichlis spicata	3.31	Lanning & Eleuterius (1981)	
Distichlis spicata	3.85	Lanning & Eleuterius (1983)	
Dryopteris bissetiana	0.13	Ma & Takahashi (2002)	
Dryopteris carthusiana	0.24	Höhne & Richter (1981)	

Dryopteris carthusiana	0.98	Höhne & Richter (1981)
Dryopteris crassirhizoma	0.30	Ma & Takahashi (2002)
Dryopteris erythrosora	0.45	Ma & Takahashi (2002)
Dryopteris filix-mas	0.13	Höhne (1963)
Dryopteris filix-mas	0.15	Höhne (1963)
Dryopteris filix-mas	0.11	Höhne (1963)
Dryopteris filix-mas	0.06	Höhne (1963)
Dryopteris filix-mas	0.13	Höhne (1963)
Dryopteris filix-mas	0.30	Höhne (1963)
Dryopteris filix-mas	0.64	Höhne & Richter (1981)
Dryopteris filix-mas	0.51	Höhne & Richter (1981)
Dryopteris lacera	0.41	Ma & Takahashi (2002)
Dryopteris sieboldii	0.58	Ma & Takahashi (2002)
Dryopteris uniformis	0.51	Ma & Takahashi (2002)
Ecballium elaterium	1.22	Ma & Takahashi (2002)
Echinochloa colona	0.62	Cowgill (1989)
Echinochloa crus-galli	2.22	Lanning & Eleuterius (1983)
Echinochloa crus-galli	3.65	Lanning & Eleuterius (1987)
Echium angustifolium	1.13	Cowgill (1989)
Eclipta erecta	0.46	Cowgill (1989)
Ehrharta erecta	1.82	Barbehenn (1993)
Elaeagnus multiflora	0.34	Ma & Takahashi (2002)
Eleocharis cellulosa	2.67	Lanning & Eleuterius (1983)
Eleocharis parvula	6.13	Lanning & Eleuterius (1983)
Eleocharis uniglumis	14.98	Tyler (1971)
Elymus cinereus	2.10	Bezeau et al. (1996)
Elymus elymoides	1.60	Blank et al. (1994)
Elymus elymoides	3.20	Blank et al. (1994)
Elymus innovatus	2.13	Bezeau et al. (1996)
Elymus junceus	2.37	Bezeau et al. (1996)
Elymus junceus	2.32	Bezeau et al. (1996)
Elymus mollis	2.03	Ma & Takahashi (2002)
Elymus virginicus	4.48	Lanning & Eleuterius (1985)

Elytrigia atherica	3.42	de Bakker *et al.* (1999)	
Empetrum nigrum	0.19	Carnelli et al. (2001)	
Encephalartos arenarius	0.54	This Study	Loran Whitelock
Encephalartos horridus	0.18	This Study	Huntington
Encephalartos lebomboensis	0.21	This Study	Loran Whitelock
Encephalartos longifolius	0.41	This Study	Loran Whitelock
Encephalartos natalensis	0.12	This Study	Huntington
Encephalartos sp.	0.31	This Study	Loran Whitelock
Encephalartos sp.	0.38	This Study	Loran Whitelock
Encephalartos villosus	0.42	This Study	Huntington
Encephalartos vondola	0.06	This Study	Loran Whitelock
Ephedra californicum	0.36	This Study	RSABG
Ephedra nevadensis	0.07	This Study	RSABG
Ephedra sinica	0.04	Ma & Takahashi (2002)	
Ephedra viridis	0.08	This Study	RSABG
Ephedra viridis	0.12	This Study	RSABG
Epilobium hirsutum	0.21	Cowgill (1989)	
Epimedium grandiflorum	0.83	Ma & Takahashi (2002)	
Equisetum arvense	9.09	Ma & Takahashi (2002)	
Equisetum arvense	12.84	Ma & Takahashi (2002)	
Equisetum hyemale	5.31	Ma & Takahashi (2002)	
Equisetum hyemale	12.02	Ma & Takahashi (2002)	
Equisetum hyemale	0.30	This Study	Pasadena, CA
Equisetum hyemale	7.39	This Study	Huntington
Equisetum hyemale	10.03	This Study	Huntington
Equisetum hyemale	12.38	This Study	Huntington
Equisetum hyemale	17.94	This Study	Huntington
Eragrostis curvula	1.20	Bilbro et al. (1991)	
Eranthis giganteus	3.55	Lanning & Eleuterius (1985)	
Erica canaliculata	0.34	Ma & Takahashi (2002)	
Erigeron crispus	0.11	Cowgill (1989)	
Eugenia uniflora	0.18	Pereire & Felcman (1998)	
Euonymus japonicus	0.39	Nakanishi et al. (2003)	

Eupatorium fortunei	0.79	Ma & Takahashi (2002)
Eurotia lanata	0.60	Bezeau et al. (1996)
Eurya japonica	0.33	Nakanishi et al. (2003)
Fagus sylvatica	16.05	Bartoli & Beaucire (1976)
Fagus sylvatica	23.53	Bartoli & Beaucire (1976)
Fagus sylvatica	1.35	Genßler (unpub)
Fallugia paradoxa	0.40	Bilbro *et al.* (1991)
Ferula varia	2.85	Kolesnikov & Gins (2001)
Festuca arundinacea	7.10	Butler & Hodges (1967)
Festuca arundinacea	0.48	Cowgill (1989)
Festuca arundinacea	3.54	Pahkala & Pihala (2000)
Festuca arundinacea	2.25	Saijonkari-Pahkala (2001)
Festuca arundinacea	2.39	Street (1974)
Festuca arundinacea	4.14	Street (1974)
Festuca arundinacea	0.23	Street (1974)
Festuca arundinacea	2.39	Street (1974)
Festuca arundinacea	4.14	Street (1974)
Festuca arundinacea	2.29	Tirtapradja (1971)
Festuca arundinacea	1.86	Tirtapradja (1971)
Festuca gigantea	5.13	Höhne (1963)
Festuca gigantea	5.71	Höhne (1963)
Festuca gigantea	3.96	Höhne (1963)
Festuca halleri	3.30	Carnelli et al. (2001)
Festuca idahoensis	3.59	Bezeau et al. (1996)
Festuca ovina	0.98	Cornelissen & Thompson (1997)
Festuca ovina	1.11	Cornelissen & Thompson (1997)
Festuca pratensis	2.63	Pahkala & Pihala (2000)
Festuca pratensis	2.04	Saijonkari-Pahkala (2001)
Festuca pratensis	1.59	Tirtapradja (1971)
Festuca pratensis	1.88	Tirtapradja (1971)
Festuca puccinellii	2.96	Carnelli et al. (2001)
Festuca rubra	1.54	Barbehenn (1993)
Festuca rubra	2.82	Bezeau et al. (1996)

Festuca rubra	3.17	Butler & Hodges (1967)	
Festuca rubra	1.63	de Bakker et al. (1999)	
Festuca rubra	7.06	Gadallah & Jefferies (1995)	
Festuca scabrella	3.15	Bezeau et al. (1996)	
Festuca scabrella	1.05	Johnston et al. (1967)	
Festuca scabrella	3.04	Johnston et al. (1967)	
Festuca scabriculmis	2.52	Carnelli et al. (2001)	
Festuca sylvatica	8.02	Bartoli & Beaucire (1976)	
Ficus lyrata	3.04	Lanning (1966)	
Fimbristylis spadicea	1.39	Lanning & Eleuterius (1983)	
Fimbristylis spadicea	3.27	Lanning & Eleuterius (1983)	
Foeniculum vulgare	0.14	Cowgill (1989)	
Fraxinus americana	0.42	Geis (1973)	
Fraxinus americana	0.90	Wilding & Drees (1971)	
Fraxinus oxyphylla	0.27	Cowgill (1989)	
Galega orientalis	0.34	Pahkala & Pihala (2000)	
Galega orientalis	0.27	Saijonkari-Pahkala (2001)	
Galium elongatum	0.79	Cowgill (1989)	
Galium mollugo	1.30	Hogenbirk & Sarrazin-Delay (1995)	
Gardenia jasminoides	0.33	Nakanishi et al. (2003)	
Gentiana decumbens	1.69	Kolesnikov & Gins (2001)	
Ginkgo biloba	0.11	Ma & Takahashi (2002)	
Ginkgo biloba	0.16	This Study	Pasadena, CA
Ginkgo biloba	0.39	This Study	Pasadena, CA
Ginkgo biloba	0.42	This Study	Pasadena, CA
Glaux maritima	3.00	Tyler (1971)	
Gleditsia triacanthos	0.01	Geis (1973)	
Gleichenia glauca	1.69	Ma & Takahashi (2002)	
Glinus lotoides	0.16	Cowgill (1989)	
Glycine max	1.43	Ellis et al. (1995)	
Glycine max	2.95	Ellis et al. (1995)	
Glycine max	0.02	Van der Vorm (1980)	
Glycine max	0.04	Van der Vorm (1980)	

Glycine wightii	0.20	McManus et al. (1977)	
Gnetum gnemon	0.23	This Study	Huntington
Gnetum gnemon	0.43	This Study	Huntington
Gnetum gnemon	0.64	This Study	Huntington
Gnetum gnemon	1.83	This Study	Huntington
Gossypium hirsutum	0.18	Cooper *et al.* (1948)	
Grindelia squarrosa	0.45	Lanning & Eleuterius (1989)	
Guarea macrophylla	0.20	Pereire & Felcman (1998)	
Gymnocarpium dryopteris	4.84	Höhne & Richter (1981)	
Gymnocladus dioicus	0.22	Geis (1973)	
Halodule beaudettei	1.53	Lanning & Eleuterius (1985)	
Hedysarum americanum	0.43	Bezeau et al. (1996)	
Helianthus angustifolius	1.32	Lanning & Eleuterius (1989)	
Helianthus annuus	0.05	Van der Vorm (1980)	
Helianthus annuus	0.08	Van der Vorm (1980)	
Helianthus atrorubens	1.15	Lanning & Eleuterius (1989)	
Helianthus maximilianii	5.00	Bilbro et al. (1991)	
Helianthus tuberosus	4.80	Lanning & Eleuterius (1989)	
Helictotrichon pratense	1.48	Cornelissen & Thompson (1997)	
Helictotrichon pratense	1.75	Cornelissen & Thompson (1997)	
Heliotropium supinum	0.44	Cowgill (1989)	
Heloniopsis orientalis	0.24	Ma & Takahashi (2002)	
Hemerocallis fulva	0.39	Ma & Takahashi (2002)	
Hibiscus cannabinus	0.30	Bilbro et al. (1991)	
Hibiscus moscheutos	1.61	Lanning & Eleuterius (1985)	
Hibiscus sabdariffa	0.70	Bilbro et al. (1991)	
Hibiscus syriacus	0.39	Ma & Takahashi (2002)	
Hilaria jamesii	5.18	Smith et al. (1971)	
Hilaria rigida	4.43	Wallace et al. (1976)	
Hilaria rigida	1.99	Wallace et al. (1976)	
Hippophae rhamnoides	5.01	Kolesnikov & Gins (2001)	
Hirschfeldia incana	0.39	Cowgill (1989)	
Holcus lanatus	1.75	Cornelissen & Thompson (1997)	

Hordeum vulgare	13.30	Bilbro et al. (1991)
Hordeum vulgare	0.67	Grosse-Brauckmann (1953)
Hordeum vulgare	1.95	Grosse-Brauckmann (1953)
Hordeum vulgare	3.40	McManus et al. (1977)
Hordeum vulgare	6.13	Saijonkari-Pahkala (2001)
Hordeum vulgare	3.10	Wallace (1989)
Hordeum vulgare	2.37	Wallace (1989)
Hordeum vulgare	2.65	Wallace (1989)
Hordeum vulgare	2.27	Wallace (1989)
Hordeum vulgare	3.08	Wallace (1989)
Hordeum vulgare	6.97	Wallace (1989)
Hordeum vulgare	4.28	Wallace (1989)
Hordeum vulgare	3.81	Wallace (1989)
Hordeum vulgare	8.02	Wallace (1989)
Hordeum vulgare	2.65	Wallace (1989)
Hordeum vulgare	2.78	Wallace (1989)
Hordeum vulgare	2.48	Wallace (1989)
Hordeum vulgare	3.85	Wallace et al. (1976)
Hordeum vulgare	1.78	Wallace et al. (1976)
Hosta longissima	0.19	Ma & Takahashi (2002)
Houttuynia cordata	2.46	Ma & Takahashi (2002)
Hybanthus glutinosus	0.58	Ma & Takahashi (2002)
Hydrangea macrophylla	0.73	Ma & Takahashi (2002)
Hydrangea macrophylla	0.97	Nakanishi et al. (2003)
Hydrocotyle bonariensis	0.08	Lanning & Eleuterius (1983)
Idesia polycarpa	0.54	Nakanishi et al. (2003)
Ilex aquifolium	0.21	Ma & Takahashi (2002)
Ilex integra	0.45	Nakanishi et al. (2003)
Ilex latifolia	0.32	Nakanishi et al. (2003)
Imperata cylindrica	1.34	Lanning & Eleuterius (1989)
Inula graveolens	0.46	Cowgill (1989)
Inula helenium	2.20	Kolesnikov & Gins (2001)
Inula viscosa	0.26	Cowgill (1989)

Ipomoea sagittata	0.47	Lanning & Eleuterius (1983)	
Iris ensata	0.32	Ma & Takahashi (2002)	
Iris florentina	0.17	Ma & Takahashi (2002)	
Iris setosa	0.39	Ma & Takahashi (2002)	
Iva frutescens	1.85	Lanning & Eleuterius (1983)	
Juglans cinerea	0.48	Geis (1973)	
Juglans nigra	0.28	Geis (1973)	
Juncus effusus	1.28	Ma & Takahashi (2002)	
Juncus gerardii	3.00	Tyler (1971)	
Juncus polycephalus	0.19	Lanning & Eleuterius (1985)	
Juncus roemerianus	0.45	Lanning & Eleuterius (1983)	
Juncus roemerianus	0.34	Lanning & Eleuterius (1983)	
Juniperus communis	0.04	Hodson et al. (1997)	
Juniperus nana	0.08	Carnelli et al. (2001)	
Juniperus sp.	0.25	This Study	Caltech
Juniperus sp.	0.42	This Study	Pasadena, CA
Juniperus virginiana	0.10	Lanning & Eleuterius (1983)	
Kalanchoe braziliensis	0.07	Pereire & Felcman (1998)	
Kerria japonica	0.71	Ma & Takahashi (2002)	
Kickxia spuria	0.51	Cowgill (1989)	
Kochia scoparia	1.50	Bilbro et al. (1991)	
Koeleria cristata	2.04	Bezeau et al. (1996)	
Kosteletzkya virginica	1.33	Lanning & Eleuterius (1983)	
Lactuca serriola	0.50	Cowgill (1989)	
Larix decidua	1.09	Carnelli et al. (2001)	
Larix decidua	2.21	Hodson et al. (1997)	
Larix decidua	1.37	Klein & Geis (1978)	
Larix laricina	0.24	Klein & Geis (1978)	
Lastrea limbosperma	1.84	Höhne & Richter (1981)	
Lastrea limbosperma	2.74	Höhne & Richter (1981)	
Lastrea oligophlebia	2.61	Ma & Takahashi (2002)	
Lathyrus ochroleucus	0.77	Bezeau et al. (1996)	
Lavandula angustifolia	1.16	Ma & Takahashi (2002)	

Leontodon hispidus	0.41	Cornelissen & Thompson (1997)
Leptogramma mollissima	6.42	Ma & Takahashi (2002)
Ligustrum japonicum	0.48	Nakanishi et al. (2003)
Ligustrum lucidum	0.43	Nakanishi et al. (2003)
Lilaeopsis chinensis	4.12	Lanning & Eleuterius (1983)
Lilium leichtlinii	0.24	Ma & Takahashi (2002)
Limonium carolinianum	0.44	Lanning & Eleuterius (1981)
Limonium vulgare	0.00	de Bakker et al. (1999)
Lindera benzoin	0.08	Geis (1973)
Lindera strychnifolia	0.19	Ma & Takahashi (2002)
Linum usitatissimum	0.10	Saijonkari-Pahkala (2001)
Liriodendron tulipifera	1.53	Nakanishi *et al.* (2003)
Lobelia cardinalis	0.04	Lanning & Eleuterius (1983)
Loiseleuria procumbens	0.32	Carnelli et al. (2001)
Lolium perenne	13.20	Butler & Hodges (1967)
Lolium perenne	0.93	Reay & Bennett (1987)
Lolium rigidum	1.58	Grosse-Brauckmann (1953)
Lolium rigidum	1.23	Grosse-Brauckmann (1953)
Lolium rigidum	1.40	Grosse-Brauckmann (1953)
Lolium rigidum	2.34	Jones & Handreck (1967)
Lotus corniculatus	0.11	Cornelissen & Thompson (1997)
Lotus corniculatus	0.60	Hogenbirk & Sarrazin-Delay (1995)
Loxogramme saziran	0.26	Ma & Takahashi (2002)
Ludwigia stolonifera	0.13	Cowgill (1989)
Luffa acutangula	1.11	Ma & Takahashi (2002)
Lupinus argenteus	0.86	Bezeau et al. (1996)
Lupinus nanus	0.24	Grosse-Brauckmann (1953)
Lupinus nanus	0.16	Grosse-Brauckmann (1953)
Luzula luzuloides	0.94	Höhne (1963)
Luzula luzuloides	0.43	Höhne (1963)
Luzula luzuloides	1.16	Höhne (1963)
Lycopersicon esculentum	0.17	Wallace (1989)
Lycopersicon esculentum	0.15	Wallace (1989)

Lycopodium carolinianum	1.20	Lanning & Eleuterius (1983)	
Lycopodium clavatum	1.37	Ma & Takahashi (2002)	
Lycopodium lucidulum	0.81	This Study	Commercial
Lycopodium lucidulum	0.91	This Study	Commercial
Lycopus europaeus	0.22	Cowgill (1989)	
Lycoris radiata	0.02	Ma & Takahashi (2002)	
Lycurus phleoides	4.16	Smith et al. (1971)	
Lygodium japonicum	2.57	Ma & Takahashi (2002)	
Lyonia ferruginea	0.29	Kalisz & Stone (1984)	
Lythrum lineare	0.69	Lanning & Eleuterius (1983)	
Lythrum salicaria	0.33	Cowgill (1989)	
Maclura pomifera	1.20	Geis (1973)	
Magnolia grandiflora	1.24	Lanning & Eleuterius (1983)	
Magnolia grandiflora	1.43	Ma & Takahashi (2002)	
Magnolia hypoleuca	1.38	Nakanishi et al. (2003)	
Magnolia kobus	0.95	Nakanishi et al. (2003)	
Mallotus japonicus	1.03	Ma & Takahashi (2002)	
Manisuris rugosa	6.75	Lanning & Eleuterius (1983)	
Marchantia polymorpha	11.87	Ma & Takahashi (2002)	
Matteuccia struthiopteris	4.69	Höhne & Richter (1981)	
Matteuccia struthiopteris	4.02	Höhne & Richter (1981)	
Medicago sativa	0.08	Bertrand & Ghitescu (1934)	
Medicago sativa	0.20	McManus et al. (1977)	
Medicago sativa	0.38	Saijonkari-Pahkala (2001)	
Megalodonta tripartita	0.35	Cowgill (1989)	
Melampyrum pratense	1.28	Höhne (1963)	
Melampyrum pratense	1.35	Höhne (1963)	
Melampyrum pratense	1.39	Höhne (1963)	
Melastoma candidum	0.39	Ma & Takahashi (2002)	
Melia azedarach	0.58	Ma & Takahashi (2002)	
Melica uniflora	4.04	Höhne (1963)	
Melilotus albus	0.31	Cowgill (1989)	
Melinis minutiflora	2.20	McManus *et al.* (1977)	

Melissa officinalis	0.68	Cowgill (1989)	
Melissa officinalis	3.44	Kolesnikov & Gins (2001)	
Mentha longifolia	0.36	Cowgill (1989)	
Mentha piperita	3.29	Kolesnikov & Gins (2001)	
Mercurialis perennis	0.24	Höhne (1963)	
Mercurialis perennis	0.24	Höhne (1963)	
Metasequoia glyptostroboides	0.09	This Study	Huntington
Metasequoia glyptostroboides	0.14	This Study	Huntington
Miscanthus sinensis	6.33	Ma & Takahashi (2002)	
Molinia caerulea	2.74	Höhne (1963)	
Molinia caerulea	3.08	Höhne (1963)	
Molinia caerulea	1.01	Höhne (1963)	
Morus alba	1.39	Ma & Takahashi (2002)	
Morus rubra	3.79	Geis (1973)	
Morus rubra	3.12	Lanning & Eleuterius (1985)	
Muhlenbergia richardsonis	7.34	Smith et al. (1971)	
Musa basjoo	2.31	Ma & Takahashi (2002)	
Myrica cerifera	0.03	Lanning & Eleuterius (1983)	
Myrica cerifera	0.09	Lanning & Eleuterius (1983)	
Nandina domestica	0.41	Ma & Takahashi (2002)	
Nandina domestica	0.15	Nakanishi et al. (2003)	
Nardus stricta	2.67	Carnelli et al. (2001)	
Nasturtium officinale	2.46	Kolesnikov & Gins (2001)	
Nephrolepis cordifolia	0.58	Ma & Takahashi (2002)	
Nephrolepis cordifolia	0.21	This Study	Commercial
Nephrolepis cordifolia	1.64	This Study	Commercial
Nephrolepis exaltata	1.59	This Study	Commercial
Nephrolepsis exaltata	0.11	This Study	Commercial
Nephrolepsis exaltata	0.11	This Study	Commercial
Nephrolepsis exaltata	0.32	This Study	Commercial
Nerium oleander	0.41	Cowgill (1989)	
Nerium oleander	0.39	Ma & Takahashi (2002)	
Nuphar lutea	0.27	Cowgill (1989)	

Oenothera lamarckiana	0.17	Ma & Takahashi (2002)
Olea europaea	0.28	Ma & Takahashi (2002)
Onoclea sensibilis	3.29	Ma & Takahashi (2002)
Origanum vulgare	1.58	Kolesnikov & Gins (2001)
Oryza sativa	13.48	Ma & Takahashi (2002)
Oryza sativa	16.50	McManus et al. (1977)
Oryza sativa	0.95	Van der Vorm (1980)
Oryza sativa	1.24	Van der Vorm (1980)
Oryza sativa	4.84	Wallace (1989)
Oryza sativa	3.74	Wallace (1989)
Oryzopsis asperifolia	3.50	Hogenbirk & Sarrazin-Delay (1995)
Osmanthus fragrans	0.46	Nakanishi et al. (2003)
Osmunda cinnamomea	2.25	Höhne & Richter (1981)
Osmunda gracilis	2.55	Ma & Takahashi (2002)
Osmunda japonica	11.96	Ma & Takahashi (2002)
Osmunda lancea	5.18	Lanning & Eleuterius (1983)
Osmunda regalis	1.87	Höhne & Richter (1981)
Ostrya virginiana	0.31	Geis (1973)
Panax ginseng	0.43	Ma & Takahashi (2002)
Panicum amarum	0.76	Lanning & Eleuterius (1983)
Panicum commutatum	7.95	Lanning & Eleuterius (1989)
Panicum maximum	2.40	McManus et al. (1977)
Panicum obtusum	4.41	Smith et al. (1971)
Panicum repens	1.17	Lanning & Eleuterius (1983)
Panicum repens	1.14	Lanning & Eleuterius (1989)
Panicum texanum	16.60	Bilbro et al. (1991)
Panicum virgatum	2.70	Bilbro et al. (1991)
Panicum virgatum	9.44	Geis (1978)
Panicum virgatum	2.43	Lanning & Eleuterius (1983)
Panicum virgatum	5.04	Lanning & Eleuterius (1987)
Papaver bracteatum	1.60	Ma & Takahashi (2002)
Papaver rhoeas	1.24	Ma & Takahashi (2002)
Paspalum dilatatum	3.68	Barbehenn (1993)

Paspalum urvillei	4.84	Lanning & Eleuterius (1987)	
Paspalum vaginatum	0.28	Cowgill (1989)	
Paspalum wettsteinii	2.50	McManus et al. (1977)	
Paulownia tomentosa	0.98	Nakanishi et al. (2003)	
Pelargonium graveolens	0.64	Ma & Takahashi (2002)	
Pellaea rotundifolia	1.65	This Study	Huntington
Pellaea rotundifolia	12.34	This Study	Huntington
Pennisetum clandestinum	2.12	Barbehenn (1993)	
Pennisetum clandestinum	2.09	Pereire & Felcman (1998)	
Persea palustris	3.40	Lanning & Eleuterius (1983)	
Phalaris arundinacea	5.73	Pahkala & Pihala (2000)	
Phalaris tuberosa	4.80	McManus et al. (1977)	
Phaseolus atropurpureus	0.30	McManus et al. (1977)	
Phaseolus vulgaris	1.82	Wallace et al. (1976)	
Phaseolus vulgaris	0.92	Wallace et al. (1976)	
Phegopteris connectilis	5.88	Höhne & Richter (1981)	
Phellodendron amurense	0.86	Ma & Takahashi (2002)	
Philadelphus satsumi	0.11	Ma & Takahashi (2002)	
Phleum pratense	1.59	Bezeau et al. (1996)	
Phleum pratense	4.00	Hogenbirk & Sarrazin-Delay (1995)	
Phleum pratense	1.60	Saijonkari-Pahkala (2001)	
Phlox subulata	2.37	Ma & Takahashi (2002)	
Phoenix dactylifera	0.58	Ma & Takahashi (2002)	
Phoenix roebelenii	0.64	Ma & Takahashi (2002)	
Phragmites australis	0.90	Cowgill (1989)	
Phragmites communis	5.26	Lanning & Eleuterius (1985)	
Physalis alkekengi	0.21	Ma & Takahashi (2002)	
Picea abies	0.85	Carnelli et al. (2001)	
Picea abies	1.11	Genßler (unpub.)	
Picea abies	2.57	Hodson et al. (1997)	
Picea glauca	0.76	Hodson & Sangster (1998, 2002)	
Picea glauca	1.31	Hodson & Sangster (1998, 2002)	
Picea glauca	1.05	Klein & Geis (1978)	

Picea mariana	0.17	Klein & Geis (1978)
Picea orientalis	2.16	Hodson et al. (1997)
Picea rubens	0.43	Klein & Geis (1978)
Picris echioides	0.32	Cowgill (1989)
Pieris japonica	0.20	Nakanishi et al. (2003)
Pinus armandii	0.41	Hodson et al. (1997)
Pinus banksiana	0.18	Klein & Geis (1978)
Pinus cembra	0.13	Carnelli et al. (2001)
Pinus clausa	0.43	Kalisz & Stone (1984)
Pinus contorta	0.11	Hodson et al. (1997)
Pinus cooperi	0.73	Hodson et al. (1997)
Pinus flexilis	0.13	Hodson et al. (1997)
Pinus jeffreyi	0.03	Hodson et al. (1997)
Pinus koraiensis	0.42	Hodson et al. (1997)
Pinus luchuensis	0.17	Ma & Takahashi (2002)
Pinus mugo	0.10	Carnelli et al. (2001)
Pinus palustris	1.09	Kalisz & Stone (1984)
Pinus palustris	0.71	Ma & Takahashi (2002)
Pinus parviflora	0.24	Hodson et al. (1997)
Pinus peuce	0.09	Hodson et al. (1997)
Pinus pinea	0.01	Hodson et al. (1997)
Pinus resinosa	0.08	Klein & Geis (1978)
Pinus strobiformis	0.06	Hodson et al. (1997)
Pinus strobus	0.17	Hodson & Sangster (1998)
Pinus strobus	0.40	Hodson & Sangster (1998)
Pinus strobus	0.05	Hodson et al. (1997)
Pinus strobus	0.09	Klein & Geis (1978)
Pinus sylvestris	1.07	Bartoli & Beaucire (1976)
Pinus sylvestris	0.49	Bartoli & Beaucire (1976)
Pinus sylvestris	0.17	Genßler (unpub.)
Pinus sylvestris	0.11	Hodson et al. (1997)
Pinus sylvestris	0.18	Klein & Geis (1978)
Pistia stratiotes	0.36	Ma & Takahashi (2002)

Pisum sativum	0.25	Jones & Handreck (1967)	
Pittosporum tobira	0.15	Nakanishi et al. (2003)	
Plantago lagopus	0.56	Cowgill (1989)	
Plantago lanceolata	0.13	Cornelissen & Thompson (1997)	
Plantago maritima	0.26	de Bakker et al. (1999)	
Platanus occidentalis	0.42	Geis (1973)	
Plectranthus japonicus	0.15	Ma & Takahashi (2002)	
Pleioblastus chino	11.06	Ma & Takahashi (2002)	
Pluchea purpurascens	0.41	Lanning & Eleuterius (1983)	
Poa chaixii	0.75	Höhne (1963)	
Poa chaixii	0.94	Höhne (1963)	
Poa compressa	2.50	Hogenbirk & Sarrazin-Delay (1995)	
Poa pratensis	1.98	Butler & Hodges (1967)	
Poa pratensis	0.28	Street (1974)	
Poa pratensis	3.63	Street (1974)	
Poa pratensis	3.66	Street (1974)	
Poa pratensis	6.10	Street (1974)	
Poa pratensis	6.10	Street (1974)	
Poa pratensis	3.48	Taber et al. (2002)	
Poa secunda	2.63	Bezeau et al. (1996)	
Podocarpus gracilior	0.10	This Study	Huntington
Podocarpus gracilior	0.34	This Study	Huntington
Podocarpus gracilior	0.44	This Study	Huntington
Podocarpus nagi	0.10	This Study	Huntington
Podocarpus nagi	0.15	This Study	Huntington
Podocarpus nagi	0.17	This Study	Huntington
Podocarpus neriifolius	0.12	Lanning (1966)	
Polygonatum odoratum	0.19	Ma & Takahashi (2002)	
Polygonum acuminatum	0.39	Cowgill (1989)	
Polygonum arenastrum	0.12	Cowgill (1989)	
Polygonum aviculare	4.21	Kolesnikov & Gins (2001)	
Polygonum fagopyrum	0.04	Bertrand & Ghitescu (1934)	
Polygonum hydropiper	0.32	Ma & Takahashi (2002)	

Polygonum lapathifolium	0.20	Cowgill (1989)	
Polygonum patulum	0.12	Cowgill (1989)	
Polygonum punctatum	2.15	Lanning & Eleuterius (1985)	
Polygonum salicifolium	0.10	Cowgill (1989)	
Polygonum senegalense	0.13	Cowgill (1989)	
Polymnia uvedalia	0.98	Lanning & Eleuterius (1983)	
Polymnia uvedalia	1.48	Lanning & Eleuterius (1987)	
Polypodium vulgare	0.26	Höhne & Richter (1981)	
Polypodium vulgare	0.83	Höhne & Richter (1981)	
Polyscias filicifolia	0.11	Lanning (1966)	
Polystichopsis amabilis	0.71	Ma & Takahashi (2002)	
Polystichopsis pseudo-aristata	0.62	Ma & Takahashi (2002)	
Polystichopsis standishii	0.45	Ma & Takahashi (2002)	
Polystichum lepidocaulon	0.13	Ma & Takahashi (2002)	
Polystichum polyblepharum	0.15	Ma & Takahashi (2002)	
Polystichum pseudo-makinoi	0.79	Ma & Takahashi (2002)	
Polystichum tripteron	0.41	Ma & Takahashi (2002)	
Polystichum tsussimense	2.48	This Study	Huntington
Polystichum tsussimense	11.96	This Study	Huntington
Poncirus trifoliata	1.05	Ma & Takahashi (2002)	
Populus deltoides	0.94	Geis (1973)	
Populus euphratica	0.34	Cowgill (1989)	
Populus sieboldii	0.55	Fu et al. (2001)	
Populus tremuloides	0.11	Bezeau et al. (1996)	
Potentilla erecta	2.50	Kolesnikov & Gins (2001)	
Potentilla fruticosa	0.15	Bezeau et al. (1996)	
Primula veris	2.08	Kolesnikov & Gins (2001)	
Prunus serotina	0.04	Geis (1973)	
Prunus virginiana	0.52	Geis (1973)	
Pseudolarix amabilis	0.06	Hodson et al. (1997)	
Pseudotsuga flauhauti	0.38	Hodson et al. (1997)	
Pseudotsuga macrolepis	1.93	Hodson et al. (1997)	
Pseudotsuga menziesii	0.74	Hodson et al. (1997)	

Pseudotsuga menziesii	0.37	Klein & Geis (1978)	
Psilotum nudum	0.19	This Study	Huntington
Psilotum nudum	0.19	This Study	Huntington
Pteridium aquilinum	1.24	Höhne (1963)	
Pteridium aquilinum	1.11	Höhne (1963)	
Pteridium aquilinum	1.67	Höhne (1963)	
Pteridium aquilinum	1.95	Höhne (1963)	
Pteridium aquilinum	2.44	Höhne & Richter (1981)	
Pteridium aquilinum	3.89	Höhne & Richter (1981)	
Pteridium aquilinum	10.61	Ma & Takahashi (2002)	
Pteris ensiformis	3.49	Ma & Takahashi (2002)	
Puccinellia maritima	0.53	de Bakker et al. (1999)	
Puccinellia phryganodes	0.74	Gadallah & Jefferies (1995)	
Pulicaria dysenterica	0.13	Cowgill (1989)	
Pulsatilla multifida	2.01	Kolesnikov & Gins (2001)	
Pyracantha crenulata	0.19	Ma & Takahashi (2002)	
Pyrrosia lingua	0.11	Ma & Takahashi (2002)	
Pyrrosia lingua	0.09	Ma & Takahashi (2002)	
Quercus alba	0.90	Geis (1973)	
Quercus chapmanii	0.38	Kalisz & Stone (1984)	
Quercus geminata	1.33	Kalisz & Stone (1984)	
Quercus imbricaria	0.38	Geis (1973)	
Quercus laevis	0.39	Kalisz & Stone (1984)	
Quercus macrocarpa	0.44	Geis (1973)	
Quercus muehlenbergii	0.58	Geis (1973)	
Quercus myrtifolia	0.44	Kalisz & Stone (1984)	
Quercus petraea	0.63	Genßler (unpub.)	
Quercus robur	1.84	Bartoli & Beaucire (1976)	
Quercus robur	0.62	Genßler (unpub.)	
Quercus rubra	0.15	Geis (1973)	
Quercus suber	0.73	Ma & Takahashi (2002)	
Quercus velutina	0.13	Geis (1973)	
Ranunculus japonicus	0.77	Ma & Takahashi (2002)	

Renealmia petasites	0.91	Pereire & Felcman (1998)
Rhapis humilis	1.11	Ma & Takahashi (2002)
Rhodiola linearifolia	6.29	Kolesnikov & Gins (2001)
Rhododendron ferrugineum	0.04	Carnelli et al. (2001)
Rhododendron japonicum	0.90	Ma & Takahashi (2002)
Rhododendron pulchrum	0.39	Nakanishi et al. (2003)
Rhynchospora plumosa	3.85	Lanning & Eleuterius (1989)
Rohdea japonica	0.53	Ma & Takahashi (2002)
Rosa woodsii	0.51	Bezeau et al. (1996)
Rubia tinctorum	1.07	Ma & Takahashi (2002)
Rubus idaeus	0.11	Höhne (1963)
Rubus idaeus	0.13	Höhne (1963)
Rubus idaeus	0.02	Höhne (1963)
Rubus idaeus	0.02	Höhne (1963)
Rubus idaeus	0.26	Höhne (1963)
Rumex dentatus	0.10	Cowgill (1989)
Ruppia maritima	3.20	Lanning & Eleuterius (1985)
Sabal etonia	3.14	Kalisz & Stone (1984)
Sabal minor	2.11	Lanning & Eleuterius (1983)
Saccharum officinarum	1.75	Lanning & Eleuterius (1985)
Saccharum officinarum	1.65	Ma & Takahashi (2002)
Saccharum officinarum	0.32	Van der Vorm (1980)
Saccharum officinarum	0.90	Van der Vorm (1980)
Sagittaria lancifolia	0.27	Lanning & Eleuterius (1983)
Sagittaria trifolia	0.83	Ma & Takahashi (2002)
Salicornia bigelovii	0.74	Lanning & Eleuterius (1985)
Salicornia europaea	0.00	de Bakker et al. (1999)
Salicornia virginica	0.02	Lanning & Eleuterius (1985)
Salix acmophylla	0.20	Cowgill (1989)
Salix matsudana	0.30	Ma & Takahashi (2002)
Salsola kali	1.60	Bilbro et al. (1991)
Salvia officinalis	1.41	Ma & Takahashi (2002)
Sansevieria trifasciata	0.02	Ma & Takahashi (2002)

Saponaria officinalis	0.58	Ma & Takahashi (2002)	
Sasa nipponica	1.54	Fu *et al.* (2001)	
Sasa nipponica	9.24	Ma & Takahashi (2002)	
Sassafras albidum	0.07	Geis (1973)	
Saururus chinensis	0.60	Ma & Takahashi (2002)	
Schisandra chinensis	3.15	Kolesnikov & Gins (2001)	
Sciadopitys verticillata	0.13	This Study	Huntington
Scirpus americanus	2.84	Lanning & Eleuterius (1985)	
Scirpus cyperinus	3.31	Lanning & Eleuterius (1989)	
Scirpus olneyi	2.55	Lanning & Eleuterius (1983)	
Scirpus robustus	5.23	Lanning & Eleuterius (1983)	
Scirpus tabernaemontani	0.45	Ma & Takahashi (2002)	
Scirpus validus	2.37	Lanning & Eleuterius (1981)	
Secale cereale	0.49	Grosse-Brauckmann (1953)	
Secale cereale	2.41	Jones & Handreck (1967)	
Secale cereale	2.23	Ma & Takahashi (2002)	
Secale cereale	1.40	Robbins et al. (1987)	
Secale cereale	3.61	Saijonkari-Pahkala (2001)	
Securinega suffruticosa	0.41	Ma & Takahashi (2002)	
Sedum hybridum	7.68	Kolesnikov & Gins (2001)	
Selaginella caulescens	1.95	Ma & Takahashi (2002)	
Selaginella caulescens	11.32	Ma & Takahashi (2002)	
Selaginella involvens	5.54	Ma & Takahashi (2002)	
Selaginella involvens	8.37	Ma & Takahashi (2002)	
Selaginella kraussiana	2.57	This Study	Commercial
Selaginella sp.	0.69	This Study	Huntington
Selaginella sp.	1.06	This Study	Huntington
Selaginella sp.	4.14	This Study	Huntington
Selaginella uncinata	3.94	Ma & Takahashi (2002)	
Selaginella uncinata	4.08	This Study	Commercial
Senecio fuchsii	1.24	Höhne (1963)	
Senecio fuchsii	0.98	Höhne (1963)	
Senecio fuchsii	0.53	Höhne (1963)	

Senecio fuchsii	1.52	Höhne (1963)	
Sequoia sempervirens	0.51	Ma & Takahashi (2002)	
Sequoia sp.	0.15	This Study	Huntington
Sequoiadendron giganteum	0.39	Hodson et al. (1997)	
Sequoiadendron sp.	0.27	This Study	Huntington
Serenoa repens	3.67	Kalisz & Stone (1984)	
Serenoa repens	5.24	Lanning & Eleuterius (1985)	
Seriphidium maritimum	0.66	de Bakker et al. (1999)	
Setaria geniculata	3.96	Lanning & Eleuterius (1987)	
Setaria italica	0.55	Bilbro et al. (1991)	
Setaria italica	0.30	Bilbro et al. (1991)	
Setaria magna	6.06	Lanning & Eleuterius (1989)	
Setaria sphacelata	1.00	McManus et al. (1977)	
Smilacina japonica	1.16	Ma & Takahashi (2002)	
Solanum americanum	0.36	Pereire & Felcman (1998)	
Solanum nigrum	0.17	Cowgill (1989)	
Solidago sempervirens	0.22	Lanning & Eleuterius (1983)	
Sonchus oleraceus	0.28	Cowgill (1989)	
Sophora flavescens	0.11	Ma & Takahashi (2002)	
Sophora japonica	0.15	Ma & Takahashi (2002)	
Sorghastrum nutans	5.00	Geis (1978)	
Sorghastrum nutans	7.18	Lanning & Eleuterius (1987)	
Sorghum bicolor	0.57	Bilbro *et al.* (1991)	
Sorghum bicolor	0.98	Bilbro *et al.* (1991)	
Sorghum bicolor	4.26	Ellis et al. (1995)	
Sorghum bicolor	4.69	Ellis et al. (1995)	
Sorghum halepense	1.55	Lanning & Eleuterius (1985)	
Spartina alterniflora	0.83	Lanning & Eleuterius (1981)	
Spartina alterniflora	2.28	Lanning & Eleuterius (1983)	
Spartina anglica	2.61	de Bakker et al. (1999)	
Spartina cynosuroides	2.52	Lanning & Eleuterius (1983)	
Spartina cynosuroides	0.56	Lanning & Eleuterius (1989)	
Spartina patens	0.89	Lanning & Eleuterius (1983)	

Spartina patens	2.19	Lanning & Eleuterius (1983)
Spergularia media	0.00	de Bakker et al. (1999)
Sphagnum cymbifolium	2.93	Ma & Takahashi (2002)
Spiraea thunbergii	0.34	Ma & Takahashi (2002)
Spiranthes sinensis	0.13	Ma & Takahashi (2002)
Sporobolus cryptandrus	3.50	Smith *et al.* (1971)
Staphylea trifolia	0.30	Geis (1973)
Stemona japonica	0.49	Ma & Takahashi (2002)
Stipa comata	0.94	Bezeau et al. (1996)
Stipa comata	0.88	Johnston et al. (1967)
Stipa comata	1.17	Johnston et al. (1967)
Stipa comata	0.89	Johnston et al. (1967)
Stipa comata	1.50	Johnston et al. (1967)
Stipa comata	1.55	Johnston et al. (1967)
Stipa comata	1.08	Johnston et al. (1967)
Stipa comata	2.62	Johnston et al. (1967)
Stipa comata	2.54	Johnston et al. (1967)
Stipa comata	1.13	Johnston et al. (1967)
Stipa comata	1.83	Johnston et al. (1967)
Stipa comata	2.76	Lanning & Eleuterius (1987)
Stipa richardsonii	2.64	Bezeau et al. (1996)
Stipa spartea	2.86	Bezeau et al. (1996)
Stipa spartea	3.67	Lanning & Eleuterius (1987)
Stipa viridula	3.40	Bezeau et al. (1996)
Struthanthus marginatus	0.27	Pereire & Felcman (1998)
Struthiopteris niponica	6.78	Ma & Takahashi (2002)
Styrax japonicus	0.34	Nakanishi et al. (2003)
Suaeda maritima	0.26	de Bakker et al. (1999)
Symphoricarpos occidentalis	1.05	Bezeau et al. (1996)
Tamarix chinensis	1.16	Ma & Takahashi (2002)
Tamarix jordanis	0.19	Cowgill (1989)
Taxodium distichum	0.08	Hodson et al. (1997)
Taxodium japonicum	0.07	Fu et al. (2001)

Taxus baccata	0.16	Hodson et al. (1997)
Taxus cuspidata	0.51	Hodson et al. (1997)
Ternstroemia japonica	0.32	Nakanishi et al. (2003)
Thea sinensis	0.12	Fu et al. (2001)
Thea sinensis	0.09	Ma & Takahashi (2002)
Thuja orientalis	0.06	Hodson et al. (1997)
Thuja orientalis	0.43	Ma & Takahashi (2002)
Thymus marschallianus	4.73	Kolesnikov & Gins (2001)
Tibouchina pulchra	0.03	Pereire & Felcman (1998)
Tilia americana	0.49	Geis (1973)
Tillandsia usneoides	0.44	Lanning & Eleuterius (1983)
Torreya nucifera	0.24	Ma & Takahashi (2002)
Trachycarpus fortunei	3.02	Ma & Takahashi (2002)
Tradescantia ohiensis	0.83	Ma & Takahashi (2002)
Trichachne californica	2.70	Bilbro et al. (1991)
Tricyrtis hirta	0.51	Ma & Takahashi (2002)
Trifolium fragiferum	0.14	Cowgill (1989)
Trifolium hybridum	0.80	Hogenbirk & Sarrazin-Delay (1995)
Trifolium incarnatum	0.12	Jones & Handreck (1967)
Trifolium pratense	0.12	Grosse-Brauckmann (1953)
Trifolium pratense	0.10	Grosse-Brauckmann (1953)
Trifolium pratense	0.09	Grosse-Brauckmann (1953)
Trifolium pratense	0.70	Hogenbirk & Sarrazin-Delay (1995)
Trifolium pratense	0.30	McManus et al. (1977)
Trifolium pratense	0.31	Saijonkari-Pahkala (2001)
Trifolium repens	1.00	Hogenbirk & Sarrazin-Delay (1995)
Trifolium repens	0.11	Reay & Bennett (1987)
Trifolium subterraneum	3.10	McManus et al. (1977)
Triglochin maritima	0.00	de Bakker et al. (1999)
Triglochin maritima	2.40	Tyler (1971)
Triglochin striata	1.20	Lanning & Eleuterius (1983)
Trilisa odoratissima	0.77	Lanning & Eleuterius (1985)
Tripsacum dactyloides	0.93	Lanning & Eleuterius (1983)

Triticosecale spp.	5.90	Bilbro et al. (1991)	
Triticum aestivum	10.74	Bilbro *et al.* (1991)	
Triticum aestivum	2.16	Cooper et al. (1948)	
Triticum aestivum	0.96	Grosse-Brauckmann (1953)	
Triticum aestivum	3.08	Ma & Takahashi (2002)	
Triticum aestivum	5.60	McManus et al. (1977)	
Triticum aestivum	2.48	Reay & Bennett (1987)	
Triticum aestivum	2.70	Robbins et al. (1987)	
Triticum aestivum	3.52	Saijonkari-Pahkala (2001)	
Triticum aestivum	5.99	Schnug & v. Franck (1985)	
Triticum aestivum	16.05	Schnug & v. Franck (1985)	
Triticum aestivum	24.18	Schnug & v. Franck (1985)	
Triticum aestivum	0.18	Van der Vorm (1980)	
Triticum aestivum	0.41	Van der Vorm (1980)	
Triticum aestivum	2.20	Wallace (1989)	
Triticum aestivum	0.90	Wallace (1989)	
Triticum boeoticum	5.58	Ma & Takahashi (2002)	
Triticum dicoccoides	2.85	Ma & Takahashi (2002)	
Triticum percicumxAegilopssquarrosa	3.64	Ma & Takahashi (2002)	
Tropaeolum majus	0.04	Ma & Takahashi (2002)	
Tsuga canadensis	0.26	Hodson et al. (1997)	
Tsuga canadensis	0.16	Klein & Geis (1978)	
Tsuga caroliniana	0.14	Klein & Geis (1978)	
Tsuga diversifolia	0.81	Hodson et al. (1997)	
Tsuga heterophylla	0.23	Hodson et al. (1997)	
Typha angustata	0.20	Cowgill (1989)	
Typha angustifolia	0.04	Lanning & Eleuterius (1983)	
Ulmus americana	3.30	Geis (1973)	
Ulmus americana	5.10	Lanning (1966)	
Ulmus rubra	2.14	Geis (1973)	
Uniola paniculata	0.38	Lanning & Eleuterius (1983)	
Uniola paniculata	1.58	Lanning & Eleuterius (1985)	
unknown fern	2.68	This Study	Huntington

unknown fern	7.33	This Study	Huntington
Urtica dioica	1.60	Cornelissen & Thompson (1997)	
Urtica dioica	1.13	Höhne (1963)	
Urtica dioica	4.75	Höhne (1963)	
Urtica dioica	3.74	Höhne (1963)	
Urtica dioica	2.82	Höhne (1963)	
Urtica hulensis	0.28	Cowgill (1989)	
Vaccinium myrtillus	2.14	Bartoli & Beaucire (1976)	
Vaccinium myrtillus	0.04	Carnelli et al. (2001)	
Vaccinium myrtillus	0.13	Höhne (1963)	
Vaccinium myrtillus	0.11	Höhne (1963)	
Vaccinium myrtillus	0.15	Höhne (1963)	
Vaccinium myrtillus	0.19	Höhne (1963)	
Vaccinium myrtillus	0.24	Höhne (1963)	
Vaccinium myrtillus	0.30	Höhne (1963)	
Vaccinium uliginosum	0.10	Carnelli et al. (2001)	
Vaccinium vitis-idaea	0.04	Carnelli et al. (2001)	
Valeriana officinalis	2.08	Kolesnikov & Gins (2001)	
Verbena officinalis	0.46	Cowgill (1989)	
Verbena officinalis	1.01	Ma & Takahashi (2002)	
Vicia americana	0.41	Bezeau et al. (1996)	
Vicia villosa	0.02	Fu *et al.* (2001)	
Viola tricolor	0.28	Ma & Takahashi (2002)	
Vitex agnus-castus	0.56	Cowgill (1989)	
Vitis aestivalis	0.34	Lanning & Eleuterius (1983)	
Wasabia japonica	0.30	Ma & Takahashi (2002)	
Washingtonia filifera	3.05	Lanning (1966)	
Welwitschia mirabilis	0.33	This Study	Huntington
Wisteria brachybotrys	0.51	Ma & Takahashi (2002)	
Wollemia nobilis	0.20	This Study	Huntington
Wollemia nobilis	0.36	This Study	Huntington
Woodwardia orientalis	5.03	Ma & Takahashi (2002)	
Xanthium strumarium	0.32	Cowgill (1989)	

Yucca aloifolia	0.03	Lanning & Eleuterius (1983)
Yucca filamentosa	0.17	Ma & Takahashi (2002)
Zamioculcas zamiifolia	0.46	Lanning (1966)
Zanthoxylum americanum	0.44	Geis (1973)
Zanthoxylum piperitum	0.77	Ma & Takahashi (2002)
Zea mays	1.71	Ellis et al. (1995)
Zea mays	2.44	Ellis et al. (1995)
Zea mays	1.82	Wallace (1989)
Zea mays	1.77	Wallace (1989)
Zea mays	1.95	Wallace (1989)
Zea mays	2.17	Wallace (1989)
Zea mays	1.54	Wallace (1989)
Zea mays	1.54	Wallace (1989)
Zea mays	1.27	Wallace (1989)
Zea mays	1.43	Wallace (1989)
Zea mays	1.68	Wallace (1989)
Zea mays	1.30	Wallace (1989)
Zea mays	1.39	Wallace (1989)
Zea mays	1.56	Wallace (1989)
Zephyranthes candida	0.21	Ma & Takahashi (2002)
Zingiber mioga	0.47	Ma & Takahashi (2002)
Zizania aquatica	6.00	Lanning & Eleuterius (1981)
Zizania aquatica	4.15	Lanning & Eleuterius (1983)
Zizaniopsis miliacea	7.37	Lanning & Eleuterius (1983)
Zoysia japonica	2.85	Butler & Hodges (1967)

Supplemental Table 2: Top z-score matched protein structure for all I-TASSER NIP structural models.

NIP Type	**Modeled Protein**	**Top Z-score Match**
NIP I	At_NP_198598_1.pdb	1J4N
NIP I	Hv_BAJ96213.pdb	2W1P
NIP I	Os_EEC78689.pdb	2W1P
NIP I	Ps_CAB45652_1.pdb	1J4N
NIP II	Ea_CCI55658_1.pdb	4NEF
NIP II	Os_NP_001041813_1.pdb	2W1P
NIP II	Pp_XP_001779449_1.pdb	1J4N
NIP II	Sm_XP_002963220_1.pdb	2D57
NIP III	Ca_CAG34223.pdb	1J4N
NIP III	Cm_BAK09176.pdb	3GD8
NIP III	Hv_BAH24163_1.pdb	2B6P
NIP III	OS_NP_001048108_1.pdb	2B6P