

Initial Events during the Evolution of C₄ Photosynthesis in C₃ Species of *Flaveria*^{1[W][OPEN]}

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The evolution of C₄ photosynthesis in many taxa involves the establishment of a two-celled photorespiratory CO₂ pump, termed C₂ photosynthesis. How C₃ species evolved C₂ metabolism is critical to understanding the initial phases of C₄ plant evolution. To evaluate early events in C₄ evolution, we compared leaf anatomy, ultrastructure, and gas-exchange responses of closely related C₃ and C₂ species of *Flaveria*, a model genus for C₄ evolution. We hypothesized that *Flaveria pringlei* and *Flaveria robusta*, two C₃ species that are most closely related to the C₂ *Flaveria* species, would show rudimentary characteristics of C₂ physiology. Compared with less-related C₃ species, bundle sheath (BS) cells of *F. pringlei* and *F. robusta* had more mitochondria and chloroplasts, larger mitochondria, and proportionally more of these organelles located along the inner cell periphery. These patterns were similar, although generally less in magnitude, than those observed in the C₂ species *Flaveria angustifolia* and *Flaveria sonorensis*. In *F. pringlei* and *F. robusta*, the CO₂ compensation point of photosynthesis was slightly lower than in the less-related C₃ species, indicating an increase in photosynthetic efficiency. This could occur because of enhanced refixation of photorespired CO₂ by the centripetally positioned organelles in the BS cells. If the phylogenetic positions of *F. pringlei* and *F. robusta* reflect ancestral states, these results support a hypothesis that increased numbers of centripetally located organelles initiated a metabolic scavenging of photorespired CO₂ within the BS. This could have facilitated the formation of a glycine shuttle between mesophyll and BS cells that characterizes C₂ photosynthesis.

C₄ photosynthesis reduces the deleterious effects of photorespiration by localizing Rubisco to an internal compartment into which CO₂ is concentrated. It has independently evolved more than 62 times in the plant kingdom, making it one of the most convergent of complex traits in the biosphere (Sage et al., 2011a). Studies of C₄ evolution have led to conceptual models proposing a stepwise origin of the C₄ pathway (Monson and Rawsthorne, 2000; Sage et al., 2012). These models are based on physiological and phylogenetic research with genera that include C₃, C₄, and C₃-C₄ intermediate species (Brown et al., 1983; Hattersley et al., 1986; Ku et al., 1991; McKown et al., 2005; Marshall et al., 2007; Muhaidat et al., 2011; Sage et al., 2011b; Christin et al., 2012). Comparisons between groups indicate that

photorespiratory CO₂ recycling, termed C₂ photosynthesis, is an important intermediate phase in the evolution of C₄ photosynthesis in many of the C₄ lineages (Monson and Rawsthorne, 2000; Sage et al., 2012). In C₂ photosynthesis, the photorespiratory enzyme glycine decarboxylase (GDC) is localized to an interior compartment, generally the inner half of bundle sheath (BS) cells. GDC is a mitochondria-specific enzyme, and its location within the BS of C₂ species is due to the positioning of most mitochondria along the centripetal wall of the BS cells. This shift in GDC expression forces Gly formed during photorespiration in the mesophyll (M) to migrate into the inner BS for metabolic processing by GDC (Monson et al., 1984; Monson and Rawsthorne, 2000). Under conditions promoting photorespiration, as would occur in hot environments, substantial amounts of CO₂ are released in the BS, raising its CO₂ concentration two to four times above the atmospheric value (Bauwe et al., 1987; von Caemmerer, 1989). Chloroplast numbers are enhanced in the BS of C₂ species, and many of these occur along the inner wall in close association with the BS mitochondria (Brown and Hattersley, 1989; Rawsthorne, 1992; Marshall et al., 2007; Muhaidat et al., 2011; Sage et al., 2011b). This organelle arrangement allows for rapid reassimilation of CO₂ released by BS GDC (Monson and Rawsthorne, 2000). As a consequence, Rubisco efficiency and photosynthetic capacity are enhanced in environments promoting photorespiration (Schuster and Monson, 1990; Monson and Jaeger, 1991; Dai et al., 1996; Vogan et al., 2007).

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The evolution of the C₂ pathway has been proposed to be essential for the subsequent rise of C₄ photosynthesis, because many components of the C₄ pathway are present in C₂ plants that are closely related to C₄ species (Rawsthorne, 1992; Monson and Rawsthorne, 2000; Sage et al., 2012). For example, enlarged, Kranz-like BS cells with increased organelle number, rapid M-to-BS trafficking networks, and increased vein density are present in C₂ species (Brown et al., 1983; Brown and Hattersley, 1989; Marshall et al., 2007; McKown and Dengler, 2007; Muhaidat et al., 2011; Sage et al., 2011b). An improved understanding of why, and how, the C₂ pathway evolved could thus be important for understanding how C₄ plants originated and why they did so with such high frequency. A means to study C₂ evolution is to examine C₃ species that are closely related to C₂ species within a phylogenetic clade, for example, in *Flaveria* and *Sartwellia*, two sister genera in the subtribe Flaveriinae of the Asteraceae (McKown et al., 2005). The genus *Flaveria* has long served as the biochemical and physiological model for C₄ evolution, and its phylogenetic relationships have been resolved in recent years (Powell, 1978; Monson and Rawsthorne, 2000; McKown et al., 2005; Kapralov et al., 2011). The genus is known to contain nine C₂ species, eight C₄ species, and three accepted C₃ species (McKown et al., 2005); a fourth C₃ species, *Flaveria mcdougallii*, is of uncertain taxonomic affinity and is not available due to its rarity. The C₃ species *Flaveria cronquistii*, *Flaveria pringlei*, and *Flaveria robusta* are sister to the C₂ *Flaveria* species (Fig. 1). *F. cronquistii* branches at a basal node within the *Flaveria* phylogeny, while *F. pringlei* branches at a node between *F. cronquistii* and *F. robusta*. *F. robusta* branches between *F. pringlei* and the node where the C₂ and C₄ clades of the genus *Flaveria* arise (McKown et al., 2005). *F. pringlei*

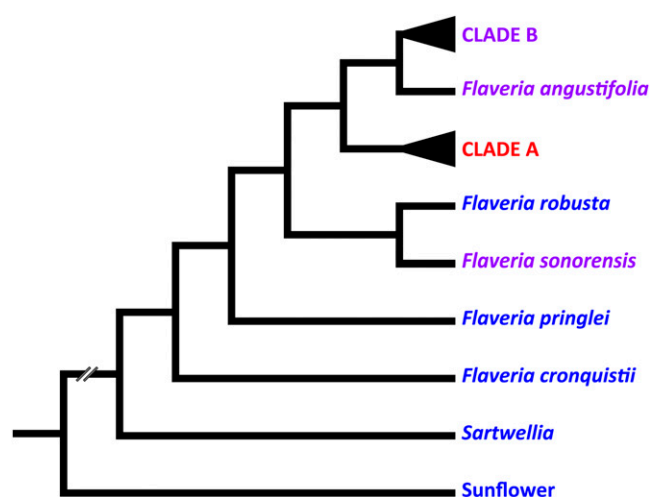


Figure 1. A simplified version of the composite Flaveriinae phylogeny of McKown et al. (2005) showing the relative branch points of the species used in this study. Species previously characterized as C₃ species are indicated in blue; C₂ species and the predominantly C₂ clade B are shown in purple; the predominantly C₄ clade A is shown in red.

and *F. robusta* may thus be good representatives of the last common ancestor between the C₃ and C₂ species within the genus *Flaveria*. Along with *Sartwellia*, the sister genus to *Flaveria*, these C₃ species represent an ideal opportunity to study trait changes within a C₃ clade where C₄ evolution was initiated.

The conclusion that *F. cronquistii*, *F. pringlei*, and *F. robusta* are functionally C₃ species is based on many gas-exchange, biochemical, and anatomical studies (Holaday et al., 1984; Brown and Hattersley, 1989; Ku et al., 1991; Dai et al., 1996; McKown and Dengler, 2007). No study has rigorously described the ultrastructure and GDC and Rubisco enzyme localization of these species, however. Such an examination is warranted given that important early events postulated for C₄ evolution may occur in BS cells during the transition from full C₃ to C₂-like photosynthesis (Sage et al., 2012). For example, in *Steinchisma laxa*, a C₃ relative of the C₂ species of *Steinchisma* (Poaceae), and in C₃ relatives of C₂ species in *Heliotropium* (Boraginaceae), BS mitochondria have shifted to the inner, centripetal pole of the BS cells (Brown et al., 1983; Muhaidat et al., 2011). C₃ *Salsola* species (Chenopodiaceae) that are closely related to C₄ clades also exhibit mitochondrial shifts to the inner BS (Voznesenskaya et al., 2013). These observations indicate that there is a distinct early phase of C₄ evolution termed “proto-Kranz,” where enlarged BS cells have increased numbers of mitochondria in a centripetal position (Muhaidat et al., 2011; Sage et al., 2012). If this is correct, then it is possible that *F. pringlei* and/or *F. robusta*, the two C₃ species of *Flaveria* that are most closely related to the C₂ species, also exhibit proto-Kranz traits. One of the C₃ *Flaveria* species (*F. pringlei*) has been noted to have high organelle numbers in the BS, although no data were presented (Holaday and Chollet, 1984). McKown and Dengler (2007), by contrast, note the BS cells of C₃ *Flaveria* species are largely free of chloroplasts.

To evaluate the early events in the evolution of C₄ photosynthesis, this research examines the cell biology and leaf gas exchange of three C₃ *Flaveria* species, two C₂ *Flaveria* species that are immediate sisters of the C₃ species, and *Sartwellia flaveriae*, from the sister genus to *Flaveria* in the Flaveriinae. We also examined the C₃ plant sunflower (*Helianthus annuus*), a fellow member of the tribe Heliantheae. We specifically evaluated the hypothesis that *F. pringlei* and *F. robusta* exhibit proto-Kranz characteristics that could be considered to be rudimentary features of C₂ metabolism, as found in the C₂ species in the study, *Flaveria angustifolia* and *Flaveria sonorensis*. If the hypothesis is supported, the results would enhance our understanding of the earliest developments in the evolution of C₄ photosynthesis and could clarify why this complex trait has evolved so frequently in the plant kingdom.

RESULTS

To statistically evaluate whether *F. pringlei* and *F. robusta* exhibit intermediate characteristics between typical

C₃ and C₂ plants, we placed the seven species of this study into three functional groups. Sunflower, *S. flaveriae*, and *F. cronquistii* represent the first group of typical or pure C₃ species. *F. pringlei* and *F. robusta* represent a second group we term proto-Kranz. *F. angustifolia* and *F. sonorensis* make up the third group of C₂ species. Data means for these functional categories are presented in Tables I and II along with the species means.

BS Anatomy and Ultrastructure

The classical view of BS cells in C₃ plants is that they are small with few organelles (Metcalf and Chalk, 1979; Sage, 2004). As a representative of a typical C₃ phenotype, we selected sunflower, which is in the same taxonomic tribe as *Flaveria* spp. and *S. flaveriae*. In sunflower, minor veins and adjacent BS cells lack prominence within the M tissue, due in part to the small size of the BS cells (Fig. 2). Sunflower BS cells are one-fourth to one-third the size of BS cells in *S. flaveriae* and *F. cronquistii*, yet they have similar organelle numbers and coverage as these Flaveriinae species (Tables I and II). The sunflower chloroplasts are preferentially in the outer half of the BS cell, where they are positioned along the intercellular air space (IAS; Fig. 2; Table II). In sunflower, similar proportions of the BS cell perimeters face M cells, IAS, other BS cells, and vascular tissue (Table I).

In *S. flaveriae* and *F. cronquistii*, BS cells are on average enlarged relative to sunflower and the other *Flaveria* species, and many of their larger BS cells extend into the IAS (Fig. 3, A and B; Table I; Supplemental Fig. S1). In *S. flaveriae*, more than one-third of the BS cell perimeter faces the IAS (Table I). In *F. cronquistii*, 16% of the BS perimeter faces the IAS. By contrast, in *F. pringlei*, *F. robusta*, *F. sonorensis*, and *F. angustifolia*, the BS cells have less IAS exposure, averaging less than 15%, while exposure of a BS cell to adjacent BS cells is high, exceeding 35% (Table I). These results indicate the BS tissue of these four *Flaveria* species form more of a radial sheath than is observed in *S. flaveriae* and *F. cronquistii*.

In the BS, chloroplast and mitochondria numbers increase in the species of this study that branch at more distal nodes in the *Flaveria* phylogeny (Table II; Fig. 1). The relative number of BS chloroplasts in the C₂ species is more than twice that in sunflower, *S. flaveriae*, and *F. cronquistii*. Chloroplast numbers in the BS of *F. pringlei* and *F. robusta* were 50% higher than in these typical C₃ species. In both the proto-Kranz and C₂ species, there are almost twice as many BS mitochondria than in the typical C₃ species (Table II). Chloroplast size differs little between the species, while mitochondria are larger in the proto-Kranz and C₂ species. These changes in number and/or size of the chloroplasts and mitochondria lead to greater coverage of the BS cell area by these organelles in cross section in the C₂ species and, in the case of mitochondrial coverage, for the proto-Kranz species as well. Unlike sunflower, the BS chloroplasts in *F. pringlei*, *F. robusta*, *F. sonorensis*, and *F. angustifolia* are evenly distributed between inner and outer halves of the BS cells (Table II). In *Flaveria* spp., there is an increase in the mitochondria numbers in the inner half of the BS cell relative to the more uniform distribution in sunflower and *S. flaveriae*. Close to 90% of the mitochondria are on the inner half of the BS cells in *F. pringlei*, *F. robusta*, *F. sonorensis*, and *F. angustifolia*, where they form a distinct row along the inner cell periphery (Table II; Figs. 3 and 4). Chloroplast coverage in the inner half of the BS exceeds 12% in the two C₂ species and averages 5.9% in *F. pringlei* and *F. robusta* (Table II). Such an aggregation is absent in the typical C₃ species, where chloroplast coverage averages 2.4% of the inner BS (Table II). In the proto-Kranz and C₂ species, the inner chloroplasts are positioned against the rank of mitochondria lining the inner BS wall (Figs. 3, C–F, and 4, C–F), in a pattern that is typical for C₂ species (Monson and Rawsthorne, 2000). In the proto-Kranz and C₂ species, the outer chloroplasts have no consistent association with mitochondria. By contrast, BS mitochondria in sunflower, *S. flaveriae*, and *F. cronquistii* are close to chloroplasts when positioned along the cell periphery

Table I. The cross-section area and perimeter of BS cells, and the percentage of BS cell perimeter in contact with other BS cells, M cells, or the IAS of five *Flaveria* species, *S. flaveriae*, and sunflower

Means ± SE are given; n = 3 to 4 plants per species. Letters indicate statistically distinct means between species or photosynthetic groups using one-way ANOVA and the Student-Newman-Keuls post-hoc test. Species means were tested separately from photosynthetic type means. PK, Proto-Kranz.

Species	Area per BS Cell	BS Cell Perimeter	Percentage of BS Cell Perimeter Facing BS	Percentage of BS Cell Perimeter Facing M	Percentage of BS Cell Perimeter Facing IAS
	μm ²	μm			
Sunflower (C ₃)	578 ± 58 a	95 ± 5 a	23.6 ± 0.6 a	25.4 ± 2.5 a	25.5 ± 0.4 b
<i>S. flaveriae</i> (C ₃)	2,221 ± 343 b	182 ± 16 b	22.8 ± 2.2 a	22.4 ± 2.9 a	37.4 ± 6.6 c
<i>F. cronquistii</i> (C ₃)	1,639 ± 405 a,b	150 ± 20 a,b	30.0 ± 2.8 a,b	38.2 ± 1.9 b	16.3 ± 4.2 a,b
C ₃ average	1,480 ± 286 x	142 ± 15 x	25.5 ± 1.5 x	28.7 ± 2.7 x	26.4 ± 3.8 y
<i>F. pringlei</i> (PK)	1,044 ± 230 a	121 ± 16 a	35.4 ± 3.5 b	37.5 ± 2.0 b	9.9 ± 3.0 a
<i>F. robusta</i> (PK)	748 ± 100 a	105 ± 8 a	37.1 ± 2.8 b,c	33.3 ± 2.7 a,b	4.5 ± 1.6 a
Proto-Kranz average	917 ± 142 x	114 ± 9 x	36.1 ± 2.2 y	35.7 ± 1.7 x	7.6 ± 2.0 x
<i>F. angustifolia</i> (C ₂)	913 ± 170 a	116 ± 7 a	45.8 ± 2.9 c	28.2 ± 3.6 a,b	6.4 ± 2.1 a
<i>F. sonorensis</i> (C ₂)	1,034 ± 53 a	124 ± 3 a	39.8 ± 1.6 b,c	27.4 ± 1.4 a	14.5 ± 2.5 a,b
C ₂ average	983 ± 74 x	121 ± 4 x	42.4 ± 1.8 z	27.7 ± 1.6 x	11.1 ± 2.3 x

Table II. Characteristics of bundles sheath organelles from sunflower, *S. flaveriae*, and species of *Flaveria*

Means \pm SE are given; $n = 3$ to 4 plants per species. Letters indicate statistically distinct means via one-way ANOVA and the Student-Newman-Keuls post-hoc test ($P < 0.05$). Species means were tested separately from photosynthetic type means. PK, Proto-Kranz.

Species	Relative No. (per $\mu\text{m}^{-2} \times 10^{-3}$)	Size	Proportion in Inner Half of Cell	Coverage of Total Cell Area	Coverage of Inner Half of Cell Area
		μm^2	%	%	%
BS chloroplast					
Sunflower (C ₃)	8.0 \pm 1.4 a	4.8 \pm 0.5 a	21.8 \pm 3.6 a	3.9 \pm 1.0 a	1.6 \pm 0.2 a
<i>S. flaveriae</i> (C ₃)	8.6 \pm 1.0 a	4.4 \pm 0.3 a	47.1 \pm 7.3 b,c	3.8 \pm 0.6 a	2.5 \pm 0.5 a
<i>F. cronquistii</i> (C ₃)	7.9 \pm 1.1 a	4.1 \pm 0.6 a	37.8 \pm 5.9 b	3.0 \pm 0.2 a	3.1 \pm 0.6 a
C ₃ average	8.2 \pm 0.6 x	4.4 \pm 0.3 x	35.6 \pm 4.7 x	3.6 \pm 0.4 x	2.4 \pm 0.3 x
<i>F. pringlei</i> (C ₃ PK)	12.6 \pm 1.9 a	4.0 \pm 0.3 a	49.2 \pm 2.7 b,c	4.8 \pm 0.5 a	4.4 \pm 0.6 a
<i>F. robusta</i> (C ₃ PK)	13.5 \pm 2.3 a	4.7 \pm 1.4 a	56.4 \pm 2.9 c	6.9 \pm 3.3 a,b	7.9 \pm 4.3 a,b
Proto-Kranz average	13.0 \pm 1.4 y	4.3 \pm 0.6 x	52.3 \pm 2.3 y	5.7 \pm 1.3 x	5.9 \pm 1.8 y
<i>F. angustifolia</i> (C ₂)	20.1 \pm 1.5 b	5.1 \pm 0.1 a	59.7 \pm 3.7 c	10.2 \pm 0.8 b	12.1 \pm 1.2 b
<i>F. sonorensis</i> (C ₂)	21.0 \pm 1.1 b	5.6 \pm 0.2 a	60.4 \pm 2.6 d	11.5 \pm 1.0 b	15.2 \pm 1.6 b
C ₂ average	20.6 \pm 0.8 z	5.4 \pm 0.2 x	60.1 \pm 2.0 y	10.9 \pm 0.7 y	13.9 \pm 1.2 z
BS mitochondria					
Sunflower (C ₃)	15.4 \pm 3.6 a,b	0.3 \pm 0.02 a	56.7 \pm 1.9 a	0.4 \pm 0.1 a	0.4 \pm 0.1 a
<i>S. flaveriae</i> (C ₃)	7.9 \pm 0.9 a	0.4 \pm 0.04 a	52.9 \pm 10.4 a	0.3 \pm 0.1 a	0.6 \pm 0.1 a
<i>F. cronquistii</i> (C ₃)	9.1 \pm 2.7 a	0.4 \pm 0.02 a	72.5 \pm 2.9 b	0.4 \pm 0.1 a	0.5 \pm 0.2 a
C ₃ average	10.8 \pm 1.8 x	0.4 \pm 0.03 x	60.8 \pm 4.4 x	0.4 \pm 0.1 x	0.5 \pm 0.1 x
<i>F. pringlei</i> (C ₃ PK)	18.0 \pm 3.3 a,b	0.5 \pm 0.01 a	86.0 \pm 2.1 b	0.9 \pm 0.1 a,b	1.4 \pm 0.3 a,b
<i>F. robusta</i> (C ₃ PK)	18.4 \pm 3.2 a,b	0.7 \pm 0.2 a,b	90.1 \pm 3.1 b	1.2 \pm 0.1 b	2.1 \pm 0.1 b
Proto-Kranz average	18.2 \pm 2.1 y	0.6 \pm 0.1 y	87.8 \pm 1.8 y	1.0 \pm 0.1 y	1.7 \pm 0.2 y
<i>F. angustifolia</i> (C ₂)	16.3 \pm 2.3 a,b	0.7 \pm 0.1 a,b	86.3 \pm 2.2 b	1.2 \pm 0.3 b	2.1 \pm 0.6 b
<i>F. sonorensis</i> (C ₂)	22.4 \pm 2.1 b	1.0 \pm 0.1 b	89.8 \pm 1.8 b	2.1 \pm 0.2 c	4.1 \pm 0.4 c
C ₂ average	19.8 \pm 1.9 y	0.9 \pm 0.1 z	88.3 \pm 1.5 y	1.7 \pm 0.2 z	3.2 \pm 0.5 z

facing the IAS, yet they are scattered and often have no chloroplast nearby when positioned along the cell periphery facing another cell (Figs. 2 and 3, A and B).

M Properties

In all species studied, the M organelles occur on the cell periphery, usually opposite the intercellular air spaces. Mitochondria were generally associated with M chloroplasts. Organelles were equally distributed around the M cell periphery facing the IAS, demonstrating no polar separation as occurs in the BS cells of C₂ species (Supplemental Table S1). Chloroplast and mitochondrial numbers per M cell area were similar in all species. With the exception of sunflower, which had larger chloroplasts and chloroplast coverage of the M cell area, there was no significant variation between the species in chloroplast or mitochondrial coverage of the M cell area (Supplemental Table S1). These results demonstrate that observed changes in BS organelle numbers and distribution are unique to BS cells rather than reflecting altered patterning in all photosynthetic cells.

Immunolocalization of Rubisco and GDC

Immunolocalizations show the presence of the P-subunit of GDC (GDCp) and the Rubisco large subunit as brown stain corresponding to the location of either mitochondria (for GDCp) or chloroplasts (for Rubisco). The label indicating Rubisco appears throughout the leaves of

the five *Flaveria* species; however, there are distinct bands of Rubisco label around the inner BS regions in *F. pringlei* and *F. robusta* and the C₂ species *F. angustifolia* and *F. sonorensis* (Supplemental Fig. S2). Such banding is not pronounced in the inner BS of *F. cronquistii*. Immunolabel indicates that GDCp is present throughout the M tissue of *F. cronquistii*, although the label intensity is reduced in the M cells in the middle of the leaf (Fig. 5). The label for GDCp is present as distinct, punctate dots along the M cell periphery, which is consistent with the location of mitochondria in the M tissues (Muhaidat et al., 2011). BS cells lack pronounced GDCp stain in *F. cronquistii*. In *F. pringlei* and *F. robusta*, GDCp label is apparent throughout the M tissue, while in the BS, a distinct though narrow band of GDCp stain is apparent along the centripetal walls of the cells (Fig. 6, A and B); at high magnification, this GDCp label is evident as a row of punctate spots corresponding to the position of the mitochondria (Supplemental Fig. S3). The BS cells of *F. sonorensis* and *F. angustifolia* have a very pronounced band of GDCp immunolabel in the inner BS region, where the large majority of the BS mitochondria occur (Fig. 6, C and D; Supplemental Fig. S3). Both *F. sonorensis* and *F. angustifolia* exhibit punctate spots of GDCp label in the M tissue, although it is noticeably less than in the C₃ *Flaveria* species, particularly in the lower and interior regions of the M tissue (Fig. 6, C and D; Supplemental Fig. S4). By comparison, the C₂ species *Flaveria floridana* shows little GDCp immunolabel in the M tissue, in contrast to pronounced label being present in the inner BS cells (Supplemental Fig. S4E).

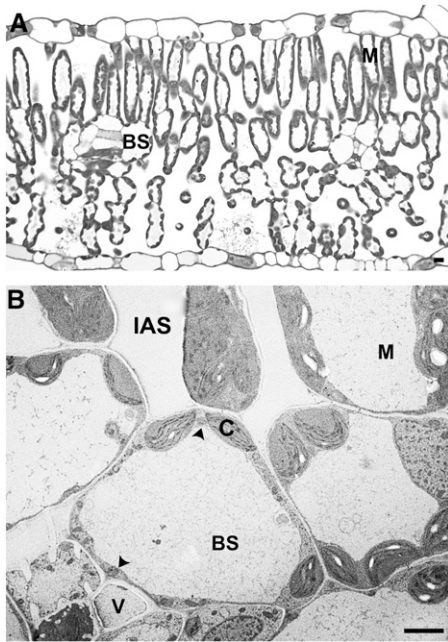


Figure 2. Light (A) and transmission (B) electron micrographs of leaf cross sections of sunflower illustrating BS cells and their organelles. Arrowheads indicate mitochondria. C, Chloroplast; M, mesophyll; V, vascular tissue. Bars = 5 μm .

Leaf Gas Exchange

The CO_2 compensation point of the net CO_2 assimilation rate (Γ) declined as light intensity increased above darkness in the C_2 , proto-Kranz, and C_3 species (Fig. 7). Each group exhibited similar Γ values at a photon flux density below $150 \mu\text{mol m}^{-2} \text{s}^{-1}$, while above $150 \mu\text{mol m}^{-2} \text{s}^{-1}$, the Γ values in the C_2 species are 35 to 39 $\mu\text{mol mol}^{-1}$ lower than in the C_3 species. At saturating light ($1,000\text{--}1,400 \mu\text{mol m}^{-2} \text{s}^{-1}$), Γ is on average 4 to 10 $\mu\text{mol mol}^{-1}$ lower in the proto-Kranz *F. pringlei* and *F. robusta* than in *F. cronquistii* and *S. flaveriae* (Fig. 7).

In the three typical C_3 species (sunflower, *S. flaveriae*, and *F. cronquistii*) and in *F. pringlei*, the response slopes of the net CO_2 assimilation rate (A) versus intercellular CO_2 content (C_i) curves determined at multiple light intensities converge upon a common value, which was used to estimate the apparent CO_2 compensation point (C^*) in the absence of apparent mitochondrial respiration in the light (R_d ; Fig. 8, A–C; data not shown for sunflower). The apparent R_d values corresponding to the species C^* estimates are indicated by dashed lines in Figure 8. In *F. robusta* and the C_2 species *F. sonorensis* and *F. angustifolia*, the A/C_i responses measured at the low to intermediate light intensities roughly converge on a common intercept, allowing for an approximate C^* estimate. The A/C_i responses at saturating light are shifted to higher A values at each C_i value, such that they do not converge on the estimated C^* but instead intercept the R_d line at a lower value than C^* (Fig. 8, D–F, compare gray and black arrows). At the estimated R_d intercept, the C_i of the high-light curves is statistically the

same as C^* in each of the C_3 species except *F. robusta*, where it is $2.6 \mu\text{mol mol}^{-1}$ less than C^* (Table III). In the C_2 species, the high-light C_i at R_d is $14.5 \mu\text{mol mol}^{-1}$ less on average than the estimated C^* (Table III). In *F. sonorensis* and *F. angustifolia*, the R_d intercept of the A/C_i response measured at $400 \mu\text{mol m}^{-2} \text{s}^{-1}$ is also shifted to a lower C_i than the estimated C^* , but only by a slight amount (Fig. 8, E and F).

DISCUSSION

In the BS cells of the species studied here, there is a change in structural traits from a typically C_3 pattern

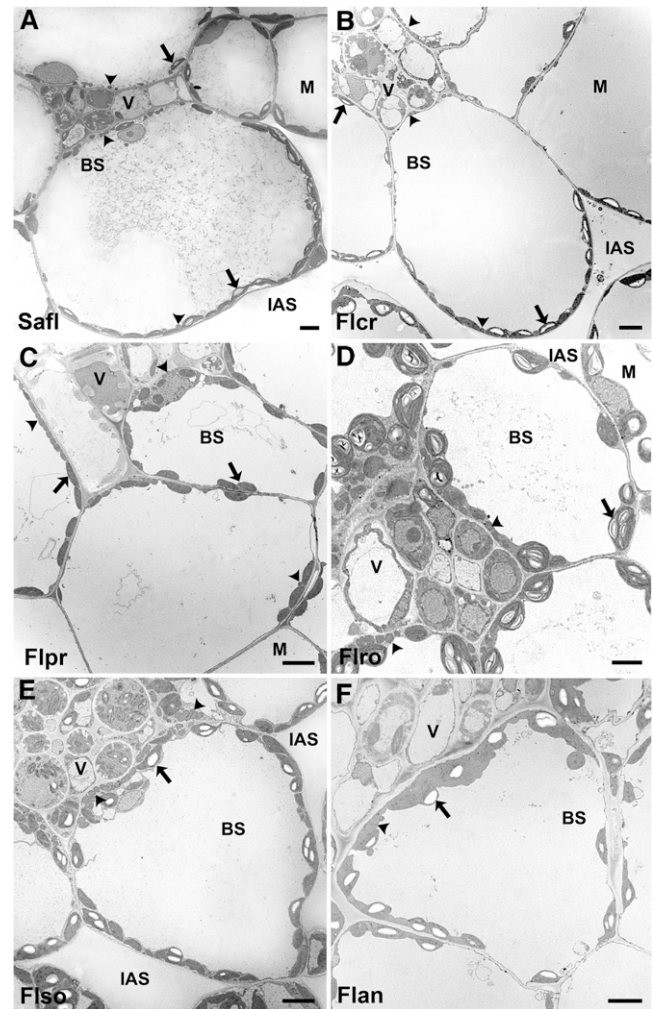


Figure 3. Transmission electron micrographs of organelle distribution in BS cells. BS chloroplasts are predominantly situated opposite vascular tissue adjacent to the IAS in *S. flaveriae* (Safi; A) and *F. cronquistii* (Flcr; B) but occupy the outer and inner cell periphery of *F. pringlei* (Flpr; C), *F. robusta* (Flro; D), *F. sonorensis* (Flso; E), and *F. angustifolia* (Flan; F). Arrows mark BS chloroplasts, and arrowheads label BS mitochondria. V, Vascular tissue. For light micrographs of BS and adjacent M tissue, see Supplemental Figure S1 and McKown and Dengler (2007). Bars = 5 μm .

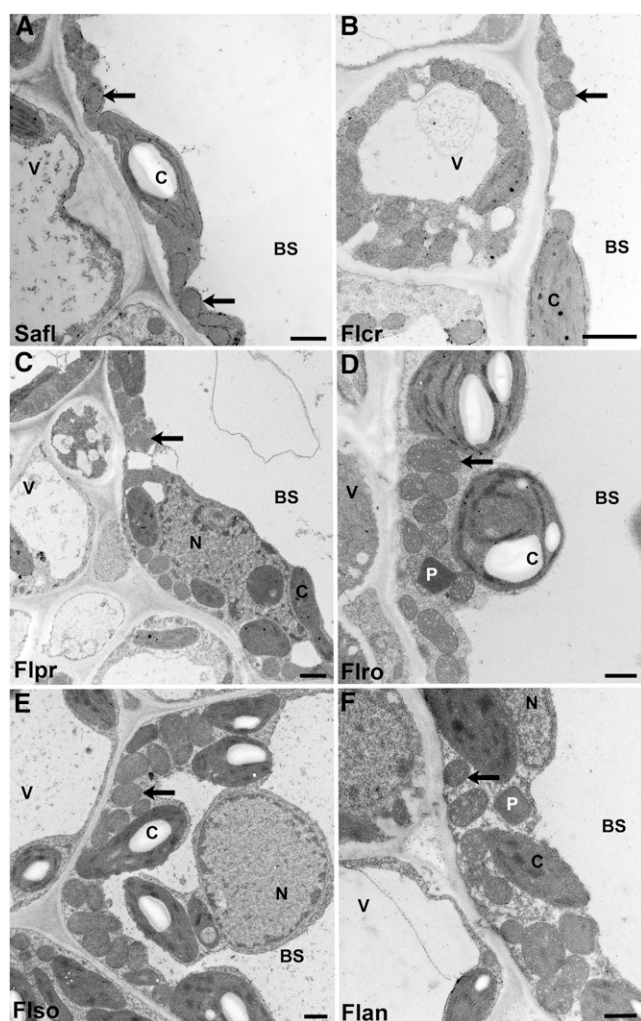


Figure 4. Transmission electron micrographs at high magnification of organelle distribution in the inner BS cells in *S. flaveriae* (Safl; A), *F. cronquistii* (Flcr; B), *F. pringlei* (Flpr; C), *F. robusta* (Flro; D), *F. sonorensis* (Flso; E), and *F. angustifolia* (Flan; F). Arrows label mitochondria. C, Chloroplast; N, nucleus; P, peroxisome; V, vascular tissue. Bars = 1 μ m.

in sunflower, *S. flaveriae*, and *F. cronquistii* to an intermediate, C₂-like pattern in *F. pringlei* and *F. robusta*. This intermediate cellular state includes an increase in organelle numbers and size as well as a shift in organelle positioning to the centripetal BS pole. These cellular traits, combined with the high vein density and large BS size reported for these species (McKown and Dengler, 2007), demonstrate that *F. pringlei* and *F. robusta* exhibit proto-Kranz features. In combination with the slight reduction in Γ and the C₁ at which the high-light A/C₁ response intercepts the apparent R_d line, these features indicate that the proto-Kranz species are intermediate between the typical C₃ and C₂ species and likely operate a weak Gly shuttle that enhances photosynthetic efficiency in the BS tissue if not the entire leaf. If the characteristics in these species reflect ancestral states,

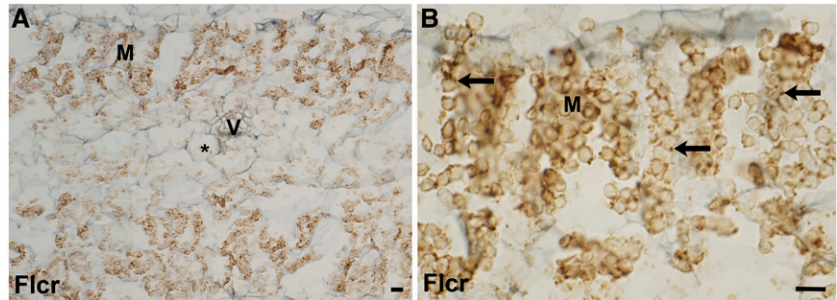
as suggested by their intermediate branching positions in the genus *Flaveria* phylogeny, the data support the hypothesis that the assembly of the C₂ pathway occurs gradually and in its incipient form may be a mechanism to scavenge photorespired CO₂. Below, we discuss the series of changes in *Flaveria* spp. that we hypothesize are the initiating steps in C₂ evolution and place these results into the context of previous studies and current models of C₄ evolution.

C₂ Photosynthesis in *Flaveria* Species

In *F. angustifolia* and *F. sonorensis*, organelle size and number are increased in the BS relative to the typical C₃ species, with a large fraction of the organelles occurring at the centripetal pole of the cells. Mitochondria, and thus GDC, are localized along the inner BS wall, where close to 90% of them occur in a line between the plasmalemma and a row of chloroplasts. This pattern is critical because it facilitates the reassimilation of photorespired CO₂ via a Gly shuttle from M cells (Hylton et al., 1988; Rawsthorne, 1992). GDC is thought to be absent in the M cells of well-developed C₂ species, perhaps as a result of a knockout mutation early in C₂ evolution (Rawsthorne, 1992; Sage et al., 2012). Consistently, GDCp is not observed in the M cells of many well-developed C₂ species, for example, in the genera *Cleome* (Marshall et al., 2007; Voznesenskaya et al., 2007), *Euphorbia* (Sage et al., 2011b), *Brassica* (Ueno, 2011), and *Heliotropium* (Muhaidat et al., 2011). In *Flaveria* spp., Hylton et al. (1988) observed no significant immunogold labeling for GDCp in M cell mitochondria of the C₂ species *Flaveria linearis* and *F. floridana*. We also observed no GDCp label in M mitochondria of *F. floridana* (Supplemental Fig. S4). Recently, it has been suggested that the loss of M GDC during C₂ evolution in *Flaveria* spp. is gradual, based on molecular data from C₂ *Flaveria chlorifolia* and *Flaveria anomala* that show partial reduction in GDCp transcript abundance in the M tissue relative to C₃ *Flaveria* species (Schulze et al., 2013). Our results with *F. angustifolia* and *F. sonorensis* support this possibility, as these two species exhibit immunostaining for GDCp in the M tissue. In the *Flaveria* spp. phylogeny, *F. sonorensis*, *F. angustifolia*, *F. anomala*, and *F. chlorifolia* branch in an intermediate position between the C₃ species and *F. linearis* and *F. floridana* (McKown et al., 2005). Thus, in *Flaveria*, GDC loss in the M tissue is incomplete in the basal-branching group of C₂ species but becomes complete in the more distal-branching *F. floridana* and *F. linearis*.

Immunolabel for GDCp is associated with GDC activity (Rawsthorne et al., 1988a, 1988b; Rawsthorne, 1992); hence, the GDCp label in the M cells of *F. angustifolia* and *F. sonorensis* indicates that GDC is still active in the M tissue. This could explain, in part, their light dependency of Γ for the following reason. At low light, Γ values converge in the C₂ and C₃ species, demonstrating a reduced level of CO₂ refixation in the C₂ species (Ku et al., 1991; Dai et al., 1996). Ribulose 1,5-bisphosphate regeneration capacity is reduced in low light, which will

Figure 5. In situ immunolocalization of GDCp in the leaf of *F. cronquistii* (Flcr). Arrows mark mitochondria, and the asterisk labels a BS cell. V, Vascular tissue. Bars = 10 μm .



reduce Rubisco oxygenase activity and, in turn, the rate of Gly formation (von Caemmerer, 1989, 2000). Residual GDC activity in the M cells of these C_2 species could metabolize much of the Gly produced at low light, thus reducing the relative flux of Gly into the BS and hence the BS CO_2 concentration. As light intensity increases, Gly production increases in the C_2 species and presumably exceeds the residual M GDC activity, thereby leading to an overflow of Gly into the BS, causing the BS CO_2 concentration to increase and Γ to decline.

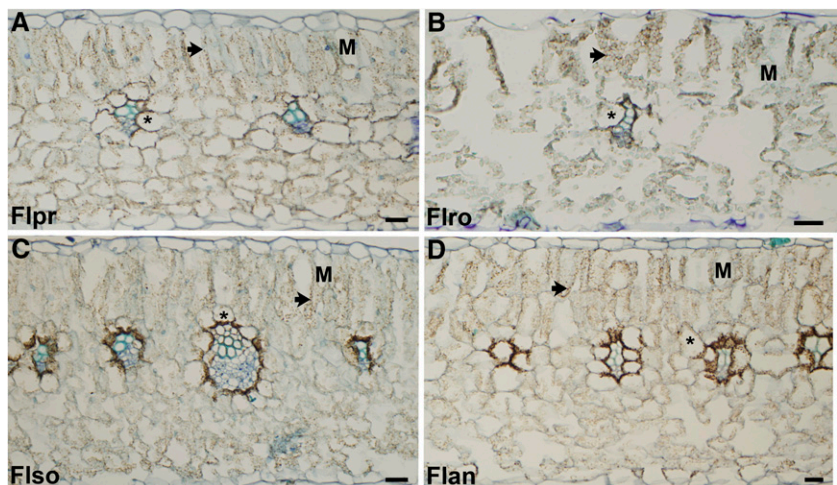
While Γ estimates from C_2 species are abundant in the literature (Monson and Rawsthorne, 2000; Vogan et al., 2007; Voznesenskaya et al., 2007), C^* estimates are rare (Voznesenskaya et al., 2010). As an indicator of photorespiratory CO_2 refixation, C^* has advantages over the commonly used parameter Γ . Rubisco carboxylation capacity, R_d , CO_2 refixation, and the oxygenation-to-carboxylation ratio of Rubisco influence Γ (Tholen et al., 2012; Busch et al., 2013), whereas C^* is largely a function of the refixation of (photo)respired CO_2 and the oxygenation-to-carboxylation ratio of Rubisco (von Caemmerer, 2000; Busch et al., 2013). All of the *Flaveria* species in this study have similar Rubisco specificity factors and, hence, similar oxygenation potentials (Kubien et al., 2008). Therefore, it can be concluded that the differences in estimated C^* between the C_3 and C_2 species reflect the greater potential for the refixation of photorespired CO_2 in the C_2 species (Bauwe et al., 1987; Monson and Rawsthorne, 2000). A previously unrecognized

response in C_2 species is the reduction in the intercept of the high-light A/C_i response with the R_d line, which is 13 to 14 $\mu\text{mol mol}^{-1}$ below the C^* estimate in both *F. angustifolia* and *F. sonorensis*. We hypothesize that this reduction in the R_d intercept at high light is caused by an increasing flux of Gly into the BS as ribulose 1,5-bisphosphate regeneration approaches its maximum capacity. Consistent with this hypothesis, we observed a slight downward shift in the R_d intercepts of the A/C_i responses measured at intermediate light intensities in the C_2 species.

F. pringlei, *F. robusta*, and the Proto-Kranz Syndrome

Compared with sunflower and *S. flaveriae*, BS mitochondria in *F. pringlei* and *F. robusta* are more numerous and have moved from an even distribution around the cell to a largely centripetal location adjacent to the vascular tissue. This aggregation creates the banding pattern of GDCp stain in the inner BS of *F. pringlei* and *F. robusta*, which is an incipient version of the dense banding produced by the numerous large mitochondria in the inner BS of C_2 species (Fig. 6; Marshall et al., 2007; Muhaidat et al., 2011; Sage et al., 2011b). Most of the inner BS chloroplasts in *F. pringlei* and to a greater extent *F. robusta* are adjacent to the row of mitochondria along the inner BS wall, in a pattern that is similar though less extensive than that of *F. sonorensis* and

Figure 6. In situ immunolocalization of GDCp in leaves of *F. pringlei* (Flpr; A), *F. robusta* (Flro; B), *F. sonorensis* (Flso; C), and *F. angustifolia* (Flan; D). Arrows mark mitochondria, and asterisks label BS cells. For high magnifications of BS and M regions, see Supplemental Figures S3 and S4, respectively. Bars = 20 μm .



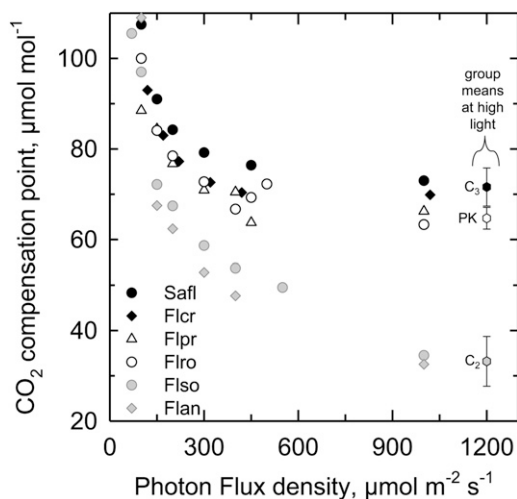


Figure 7. The light response of the CO₂ compensation point at 36°C in the C₃ species *S. flaveriae* (Safl) and *F. cronquistii* (Flcr), the proto-Kranz (PK) species *F. pringlei* (Flpr) and *F. robusta* (Flro), and the C₂ species *F. sonorensis* (Flso) and *F. angustifolia* (Flan). Symbols are averages of two to 14 observations, although most samples sizes are four to six. Error bars are shown for group means of all high-light values (1,000 and 1,400 $\mu\text{mol m}^{-2} \text{s}^{-1}$) from the C₃, proto-Kranz, and C₂ groups. These group means are statistically different at $P < 0.05$ via one-way ANOVA and Holm-Sidak post-hoc test.

F. angustifolia. Starch grains and Rubisco are abundant in the inner BS chloroplasts of *F. robusta* and the C₂ species, indicating that this region is photosynthetically active. Given the diffusive barrier represented by the vacuole, photosynthetic activity by the inner BS chloroplasts would probably depend upon (photo) respired CO₂ released by nearby mitochondria. Similar organellar traits have been observed in the C₃ grass *S. laxa* and the C₃ borages *Heliotropium karwinskyi* and *Heliotropium procumbens* (Brown et al., 1983; Muhaidat et al., 2011); these species are closely related to C₂ species in their respective clades (Aliscioni et al., 2003; Muhaidat et al., 2011). As observed for proto-Kranz *Flaveria* species, *S. laxa*, *H. karwinskyi*, and *H. procumbens* also exhibit increased BS relative to M tissue size and/or increased vein density relative to the typical C₃ condition (Morgan and Brown, 1980; Brown et al., 1983; Muhaidat et al., 2011). Notably, enlarged BS cells are a universal condition in the Flaveriinae, as indicated by the relatively large BS cells observed in *S. flaveriae* and *F. cronquistii* (McKown and Dengler, 2007). In the grasses, C₃ clades that are sister to C₄ clades also have enlarged BS, which together with the observations from *Flaveria* and *Heliotropium* species indicate that this trait may be a common exaptation facilitating the development of C₂ and C₄ photosynthesis (Sage et al., 2012; Christin et al., 2013; Griffiths et al., 2013). As indicated by *S. laxa*, it is possible that many of the grass species with enlarged BS cells may also have proto-Kranz patterns of organelle numbers and distribution.

The proto-Kranz species measured to date have slightly lower Γ than C₃ relatives at light saturation, which is consistent with modest refixation of photorespiratory CO₂ within the BS (for *S. laxa* Γ values, see Supplemental Table S3; Morgan and Brown, 1979; Vogan et al., 2007). *S. laxa* also has a partial loss of M GDCp (compared with a total loss in *Steinchisma hians*; Hylton et al., 1988). The slight reduction of the high-light A/C_i intercept with R_d that we observed in *F. robusta* is further evidence that this species has an enhanced ability to refix photorespired CO₂. Our ability to resolve this reduction in the A/C_i by R_d intercept in *F. robusta* but not *F. pringlei* probably reflects a greater refixation capacity in *F. robusta*, due to its higher organelle coverage of the inner BS. Taken together, these observations support the hypothesis that species with proto-Kranz traits operate an incipient form of C₂ photosynthesis and are, in essence, C₃-C₂ intermediates. In its rudimentary form, the C₂ cycle may largely be confined to the BS, in what may amount to a single-celled Gly shuttle. The localization of the BS mitochondria to the inner cell would

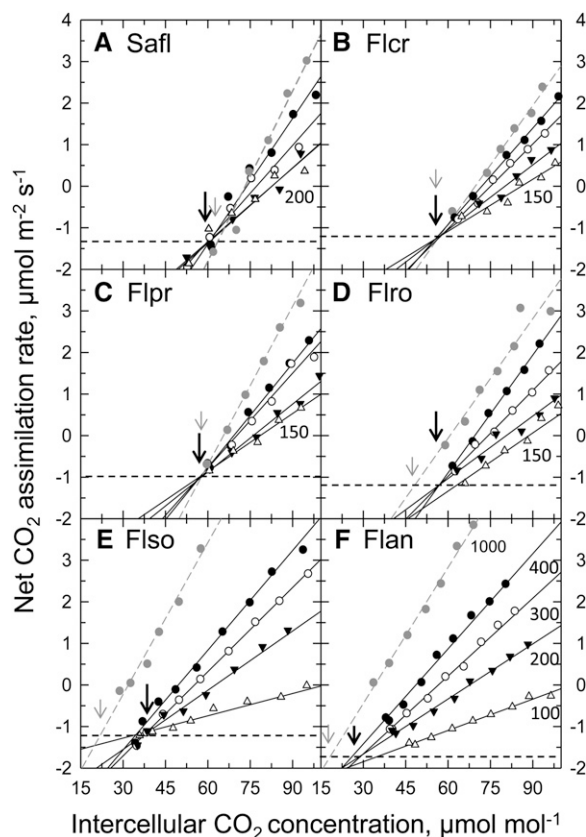


Figure 8. Representative responses of A to low C_i for *S. flaveriae* (Safl; A), *F. cronquistii* (Flcr; B), *F. pringlei* (Flpr; C), *F. robusta* (Flro; D), *F. sonorensis* (Flso; E), and *F. angustifolia* (Flan; F) at different light intensities. All responses in each panel were generated from a single leaf in a single measurement sequence, beginning with the high-light responses and ending with the lowest. Measurement light intensities are given in F or, if different, beside the respective responses.

Table III. The C_i in leaves of sunflower and species of the Flaveriinae corresponding to the point where (1) the high-light A versus C_i curve intersects the estimated R_d value, (2) multiple low-light A versus C_i curves converge at $R_d (=C^*)$, and (3) the difference between the values of 2 and 1 ($\Delta = C^* - \text{high-light } C_i \text{ at } R_d$)

Means \pm SE are given, with letters indicating statistically different groups at $P < 0.05$ by one-way ANOVA and the Student-Newman-Keuls post-hoc test. Measurements were determined at 36°C. For examples of how these values were determined, see Figure 7. Values from the C_3 species sunflower, *S. flaveriae*, and *F. cronquistii* are pooled together to give a mean of fully expressed or “typical” C_3 photosynthesis. The C_2 values are pooled from measurements of *F. sonorensis* and *F. angustifolia*. For averages of each of the species, see Supplemental Table S2. PK, Proto-Kranz.

Species	No.	High-Light C_i at R_d	C^*	Difference
Pooled C_3 average	2	60.6 \pm 0.6 c	60.0 \pm 0.6 b	-0.6 \pm 0.5 a
<i>F. pringlei</i> (PK)	5	56.9 \pm 0.9 b,c	57.1 \pm 1.3 b	0.4 \pm 0.5 a,b
<i>F. robusta</i> (PK)	15	55.0 \pm 1.1 b	57.6 \pm 1.0 b	2.6 \pm 0.6 b
Pooled C_2 average	14	22.5 \pm 1.5 a	37.0 \pm 1.4 a	14.5 \pm 0.9 c

force Gly formed in the outer BS to diffuse into the inner BS for metabolism by GDC. The large vacuole would then slow the efflux of the photorespired CO_2 , enhancing the efficiency of Rubisco in nearby chloroplasts. If the inner BS represents a large enough sink for Gly, this arrangement could also metabolize any Gly that may overflow from the M cells, such as during hot periods when photorespiration may be particularly high.

The Flaveriinae species in this study occur in semiarid landscapes of central Mexico and Texas, where summer temperatures regularly exceed 35°C, humidity is low, and drought is common (Powell, 1978; Sudderth et al., 2009). In recent geological time, heat and aridity would have combined with low atmospheric CO_2 to depress C_i and greatly increase photorespiratory potentials in the C_3 Flaveriinae species. In the late Pleistocene, for example, the combination of atmospheric CO_2 levels near 200 $\mu\text{mol mol}^{-1}$ and low stomatal conductance could have resulted in C_i values of 120 to 140 $\mu\text{mol mol}^{-1}$ in hot, low-humidity environments (Sage et al., 2012). Based on our A/C_i responses, a Γ reduction of 4 to 10 $\mu\text{mol mol}^{-1}$ would be sufficient to raise A at a C_i of 120 to 140 $\mu\text{mol mol}^{-1}$ by 15% to 20%. An improvement of A by this degree under carbon-deficient conditions should have significant consequences in terms of improved fitness and competitive ability (Gerhart and Ward, 2010).

What Facilitates the Origin of the Proto-Kranz Condition? A Working Hypothesis

As shown by sunflower, the typical BS cells in C_3 plants are relatively small, with a few centrifugal chloroplasts and little potential for refixation of photorespired CO_2 . In *S. flaveriae* and *F. cronquistii*, BS cells have become enlarged relative to sunflower and have many starch-containing chloroplasts facing the IAS, indicating that they assimilate CO_2 directly from the IAS, as is typical for M chloroplasts of C_3 plants. We conclude from this that the enlarged BS cells of these species have increased their photosynthetic engagement. Similar patterns are observed in C_3 species that

are sister to C_4 clades of the eudicot genera *Heliotropium*, *Euphorbia*, *Cleome*, *Mollugo*, and some grasses (Marshall et al., 2007; Christin et al., 2011; Muhaidat et al., 2011; Sage et al., 2011b; Christin et al., 2013). Why C_3 species may initially develop a larger BS is unclear, but it may be related to the greater vein density of leaves in hot environments with high potential evapotranspiration (Sage, 2004; Osborne and Sack, 2012). High vein density increases hydraulic flux in such environments, thereby maintaining favorable leaf water status (Roth-Nebelsick et al., 2001; Scoffoni et al., 2011; Sage et al., 2012). Increasing vein density comes at the expense of M tissue, however, which could have a photosynthetic cost. Enlarged BS cells and organelle number are often associated with high vein density in arid-zone plants such as *Flaveria* spp., leading to the hypothesis that greater size and photosynthetic engagement of BS cells compensates for a reduction of M cells (Sage et al., 2012). With more photosynthetic activity, BS cells would also photorespire more, enhancing their Gly production. In these BS cells, the movement of mitochondria and chloroplasts to the inner BS could trap photorespiratory CO_2 and thus create the weak Gly shuttle that could offset photorespiratory costs in hot, low- CO_2 environments.

In conclusion, the demonstration that the C_3 sister species of C_2 clades in the genera *Heliotropium*, *Steinchisma*, and now *Flaveria* express proto-Kranz traits is strong evidence that the proto-Kranz condition is the critical initial phase in the evolution of C_2 , and by extension, C_4 photosynthesis. Once the proto-Kranz traits are in place, benefits arising from the recycling of photorespiratory CO_2 could facilitate subsequent selection for greater flux of Gly into the inner BS. With increased organelle volume in the inner BS, there may arise a large enough sink for Gly such that a chance reduction of GDC expression in the M tissue would not be deleterious but would instead improve carbon gain in photorespiratory conditions. Upon establishment of the C_2 pathway, C_4 photosynthesis could follow because the Kranz-like features of the C_2 pathway may facilitate the up-regulation of the C_4 metabolic cycle (Sage et al., 2012). In short, the initial events that establish the proto-Kranz system could set in motion a

feed-forward, facilitation cascade that leads to C₄ photosynthesis. The high number of C₄ origins could thus reflect the relative ease of establishing the proto-Kranz condition and initiating such cascades.

MATERIALS AND METHODS

Plant Material

We studied sunflower (*Helianthus annuus*; C₃), *Sartwellia flaveriae* (C₃), and five *Flaveria* species, *Flaveria cronquistii* (C₃), *Flaveria pringlei* (C₃), *Flaveria robusta* (C₃), *Flaveria sonorensis* (C₂), and *Flaveria angustifolia* (C₂). We also included GDC immunolocalizations from *Flaveria floridana* (C₂) to facilitate comparison with the method of Hylton et al. (1988). Plants were grown from seeds or cuttings obtained from sources described in Supplemental Table S4. All plants were grown in a greenhouse in 20-L pots of a sandy-loam soil and were watered daily to avoid water stress. Fertilizer was supplied weekly as a 50:50 mixture of Miracle Grow 24-10-10 All Purpose Plant Food and Miracle Grow Evergreen Food (30-10-20) at the recommended dosage (22 mL of fertilizer salt per 6 L; Scotts Miracle-Gro; www.scotts.ca). Plants were trimmed every 4 to 8 weeks to minimize canopy crowding and maintain a balance between roots and shoots. For imaging and immunolocalizations, plants were sampled from 10 AM to 12 PM between April and October, when daylength was over 11.5 h and light intensity in the unshaded greenhouse regularly exceeded 1,400 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$. The youngest cohort of fully expanded leaves was sampled in full sun for all procedures used in the study.

Leaf Anatomy, Ultrastructure, and Immunolocalizations

The internal anatomy of leaves was assessed on sections sampled from the middle of recent, fully expanded leaves (one leaf per plant; three to four plants per species). Samples were prepared for light and transmission electron microscopy as described by Sage and Williams (1995). For fixation, a 2% (v/v) OsO₄ solution was used in C₃ species and some of the intermediates; a 1% (v/v) OsO₄ concentration had to be used in C₄ plants and some C₃-C₄ intermediates due to overly dark staining of BS cells by the 2% solution. To quantify BS and M ultrastructural parameters, transmission electron microscopy images from 10 BS and M cells from each sampled leaf were analyzed using ImageJ software (National Institutes of Health; Schneider et al., 2012).

The preparation of tissue samples for the immunolocalization of Rubisco and GDCp was performed as described by Marshall et al. (2007). Polyclonal antisera used were anti-tobacco (*Nicotiana tabacum*) Rubisco (provided by N.G. Dengler, University of Toronto) and anti-pea (*Pisum sativum*) GDC (P-subunit from S. Rawsthorne's laboratory; Hylton et al., 1988). Controls for each enzyme immunolocalization method were conducted by omitting the antisera from the procedure; these showed no background stain in any tissue (Supplemental Figs. S2 and S4).

Leaf Gas-Exchange Analysis

Gas-exchange measurements were conducted using a LI-6400 photosynthesis system (Li-Cor). The C* and R_d were estimated by measuring the response of A to C_i at multiple light intensities (Laisk, 1977; Brooks and Farquhar, 1985). Light intensities used were saturating (1,400–1,000 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$), 400, 300, 200, 150, and 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The C_i at which the initial slopes of the A/C_i responses converged was taken as an estimate of C*. The net CO₂ exchange rate corresponding to the convergence point was the estimate of R_d. All measurements were performed at 36°C to ensure high rates of Rubisco oxygenase activity. The Γ (where A is 0 $\mu\text{mol m}^{-2} \text{s}^{-1}$) as a function of light intensity was determined for each species from the A/C_i responses (Brooks and Farquhar, 1985).

Due to their relevance, we also include unpublished Γ values at two light intensities from related C₃ and C₂ *Panicum* species (now *Steinchisma* and *Panicum* species; Aliscioni et al., 2003) determined during an earlier study of C₂ plants (Supplemental Table S3; Hylton et al., 1988).

Data Analysis

Results were analyzed with Sigmaplot version 11.0 (Systat Software) using one-way ANOVA followed by the Student-Newman-Keuls multiple comparison

test. For ultrastructural analysis, leaf samples were collected from three to four plants. For each parameter, the data from the 10 sampled images per plant were averaged to give one value for a plant. These individual plant values were the unit of replication for statistical analysis. For leaf gas exchange, four to 15 measurements were conducted on four to seven plants per species.

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure S1. Leaf cross sections of species in Flaveriinae.

Supplemental Figure S2. In situ immunolocalizations of Rubisco in leaves of *Flaveria* spp.

Supplemental Figure S3. In situ immunolocalizations of the P-subunit of the glycine decarboxylase complex in BS cells of leaves from *Flaveria* spp.

Supplemental Figure S4. In situ immunolocalization of the P-subunit of the glycine decarboxylate complex in M cells of leaves from *Flaveria* spp.

Supplemental Table S1. Number, size, and distribution of M cell organelles.

Supplemental Table S2. Individual species means for high-light C_i at R_d and C*.

Supplemental Table S3. CO₂ compensation points of *Panicum* spp. and *Steinchisma* spp.

Supplemental Table S4. Collection information for species used in this study.

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