ZCN8 encodes a potential orthologue of Arabidopsis FT florigen that integrates both endogenous and photoperiod flowering signals in maize

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Abstract

Higher plants use multiple perceptive measures to coordinate flowering time with environmental and endogenous cues. Physiological studies show that florigen is a mobile factor that transmits floral inductive signals from the leaf to the shoot apex. Arabidopsis FT protein is widely regarded as the archetype florigen found in diverse plant species, particularly in plants that use inductive photoperiods to flower. Recently, a large family of FT homologues in maize, the Zea CENTRORADIALIS (ZCN) genes, was described, suggesting that maize also contains FT-related proteins that act as a florigen. The product of one member of this large family, ZCN8, has several attributes that make it a good candidate as a maize florigen. Mechanisms underlying the floral transition in maize are less well understood than those of other species, partly because flowering in temperate maize is dependent largely on endogenous signals. The maize indeterminate1 (id1) gene is an important regulator of maize autonomous flowering that acts in leaves to mediate the transmission or production of florigenic signals. This study finds that id1 acts upstream of ZCN8 to control its expression, suggesting a possible new link to flowering in day-neutral maize. Moreover, in teosinte, a tropical progenitor of maize that requires short-day photoperiods to induce flowering, ZCN8 is highly up-regulated in leaves under inductive photoperiods. Finally, vascular-specific expression of ZCN8 in Arabidopsis complements the ft-1 mutation, demonstrating that leaf-specific expression of ZCN8 can induce flowering. These results suggest that ZCN8 may encode a florigen that integrates both endogenous and environmental signals in maize.

Key words: florigen, FT orthologue, long-distance signalling, maize, photoperiod induction, teosinte, transcription factor.

Introduction

Timing of the transition from vegetative to reproductive growth in higher plants is a finely orchestrated process that is controlled through the integration of environmental cues and developmental signals. Genetic and molecular studies have defined key components that cause flowering to occur for optimal reproductive success (reviewed in Amasino and Michaels, 2010). More recently, a leaf-derived protein, identified as the product of the Arabidopsis Flowering Locus T gene (FT), has been identified and is now widely accepted as the long sought mobile florigen inferred from early physiological studies (Corbesier et al., 2007; Giakountis and Coupland, 2008). The FT protein, which encodes a phosphatidylylethanolamine-binding (PEBP)-related kinase, interacts with Flowering Locus D (FD), a bZIP protein, at the vegetative shoot apex (Abe et al., 2005; Wigge et al., 2005). The FT–FD complex subsequently activates transcription of floral meristem genes that start the flowering process, such as APETALA1 (API).

Activation of FT in response to inductive environmental cues, such as photoperiod, and subsequent movement of FT protein to the shoot apex, satisfies one of the original criteria for a florigenic substance (i.e. that it is a phloem mobile signal that passes through living tissue to its target). Another tenet of the florigen hypothesis is that the mobile inductive signal is universal and should be found in all flowering plants (Zeevaart, 1976). Although there is no...
a putative transcription factor that is a likely orthologue of FT protein that signal time to flowering. FT orthologues are being discovered in many plant species (e.g., Bohlenius et al., 2006; Gyllenstrand et al., 2007; Hayama et al., 2007; Hou and Yang, 2009; Blackman et al., 2010; Kong et al., 2010), including the grasses (Yan et al., 2006; Faure et al., 2007; Danilevskaya et al., 2008; Komiyama et al., 2008; Kikuchi et al., 2009). Therefore, the role of FT-like proteins in transmitting inductive signals in diverse plants suggests that it has a conserved ancestral function.

Genetic analyses of Arabidopsis flowering time mutants have defined a complex network of interacting flowering time genes that have orthologues in a wide variety of plants. However, given the complex nature of the floral induction process, it might be expected that other floral induction mechanisms unique to a particular subgroup, such as monocots, might have evolved that rely on pathways tailored for specific environmental conditions or developmental programmes. Indeed, many of the conserved flowering time genes first identified in Arabidopsis are present in the grasses, but some genes appear to be unique and are not present in other species (Colasanti and Coneva, 2009). In maize, only two genes have been shown to have a major effect on flowering time when mutated—indeterminate1 (id1) and delayed flowering1 (dlf1). Numerous quantitative trait loci (QTLs) associated with effects on flowering in domesticated maize have been discovered (Chardon et al., 2004; Buckler et al., 2009), but the identity of the genes underlying these QTLs has yet to be revealed.

Mutant id1 plants exhibit an extreme late flowering phenotype in which they produce more than twice as many leaves as normal maize and usually fail to form axillary ear inflorescences (Singleton, 1946; Colasanti et al., 1998). Loss-of-function dlf1 mutants exhibit a less severe flowering time defect; that is, they may produce more leaves and usually flower 1–2 weeks later than normal plants under field conditions (Neuffer et al., 1997). The id1 gene encodes a putative transcription factor that is expressed exclusively in the non-photosynthetic region of developing, immature leaves (Colasanti et al., 1998; Wong and Colasanti, 2007), whereas DLF1 is a bZIP protein that has been proposed to regulate flowering in the shoot apical region (Muszynski et al., 2006).

Functional equivalents of id1 have been identified in rice (Osld1, Ehd2, or RlD), and reduced expression or elimination of this gene was found to cause a severe delay in flowering (Matsubara et al., 2008; Park et al., 2008), or even result in rice plants that never flower (Wu et al., 2008). In dicot species, no clear orthologue of maize id1 has been identified amongst the large id1-related gene family (IDD genes) found in all higher plants (Colasanti et al., 2006), although a mutation in an Arabidopsis IDD gene was reported recently to have a minor effect on flowering time (Seo et al., 2011). Conversely, the dlf1 gene encodes a putative transcription factor that is a likely orthologue of the Arabidopsis FD gene (Muszynski et al., 2006). If DLF protein acts in a manner similar to FD, an equivalent to FT may be presumed to exist in maize as well. Maize contains a large family of FT/FL-related genes, named Zea CENTRADIALIS (ZCN) genes (Danilevskaya et al., 2008). Sequence comparisons separate the 25 ZCN genes into both FT and TFL (TERMINAL FLOWER) clades. Ectopic expression of seven ZCN genes most similar to TFL in transgenic maize showed a possible role in inhibiting flowering, therefore suggesting a role similar to that of TFL genes found in Arabidopsis and other species (Danilevskaya et al., 2010).

The question remains as to which, if any, of the maize ZCN genes have a role similar to that of Arabidopsis FT in encoding a florigen protein. The initial analysis of the maize ZCN gene family by Danilevskaya et al. (2008) pointed to ZCN8 as a strong candidate to encode an FT orthologue based on high sequence similarity to FT, a leaf-specific expression pattern, and possible interaction with DLF. To provide further evidence as to whether maize contains a putative FT-like florigen, the expression and function of the ZCN8 gene are examined here. Transcripts of the ZCN8 gene are localized to mature leaves of temperate maize and teosinte, a maize ancestor that requires short-day photoperiods to induce flowering. Inductive short-day photoperiods result in a dramatic increase in ZCN8 expression in teosinte, whereas a less prominent increase was detected in temperate maize. In addition, ZCN8 expression was found to be dependent on the activity of the id1 gene in temperate maize. Finally, evidence that ZCN8 may have the ability to act as a florigen was demonstrated by expressing it under the control of a phloem companion cell-specific promoter that completely rescued the ft mutant phenotype in Arabidopsis.

Materials and methods

Plant growth conditions and genotyping

All plants were grown in the Phytotron facility at the University of Guelph. Temperate maize (Zea mays ssp. mays; B73 inbred) and tropical maize, teosinte (Zea mays ssp parviglumis) were grown in a 2:1 mixture of Sunshine Mix and Turface clay pellets. One corner of each teosinte seed was clipped (~2 mm) to aid in germination. All plants were grown in Conviron growth chambers under full spectrum mixed fluorescent and incandescent light of 500 μmol m⁻² s⁻¹. Long-day (LD) conditions consisted of 15 h light/9 h darkness, and short-day (SD) conditions were 9 h light/15 h darkness. Day temperatures were set at 27 °C and night temperatures at 23 °C. Plants were fertilized at initial planting with 14-14-14 slow release fertilizer. Maize segregating normal (wild type; WT) and mutant allele were genotyped at the three TFL-related genes, named
LD experiments, plants were grown in light for 16 h and 8 h of darkness, while SD growth was 8 h days/16 h nights.

**Recombinant plasmid construction**

All constructs were made using Gateway® Cloning vectors and kits (Invitrogen). For all genes and promoters the pDONR-221 P4-P1r empty entry vector was used. The ZCN8 gene was amplified from cDNA derived from B73 maize leaf total RNA using primers flanking the entire coding sequence (ZmZCN8F and ZmZCN8R) (Supplementary Table S2 available at JXB online). ENTRY vector constructs were then used for Gateway recombination into the destination vector pK2GW7 for cauliflower mosaic virus (CaMV) 35S overexpression. For construction of the SUC2::ZCN8 plasmid, separate entry clones containing ZCN8 and the SUC2 promoter were recombined into plasmid pK7m24GW3 (University of Ghent, Belgium) via multi-site Gateway recombination.

**Arabidopsis transformation with Agrobacterium tumefaciens**

Transformation of WT Ler-0 and ft-1 mutant plants with Agrobacterium bacteria carrying recombinant constructs was performed using the floral dip method (Clough and Bent, 1998). For each construct, several independent lines were selected and T1 transgenic plants were analysed for flowering time and other phenotypes. CaMV35S::ZCN8 overexpression constructs were transformed into Ler-0 and ft-1 plants; SUC2::ZCN8 lines were generated in the ft-1 mutant background only.

**RNA isolation, PCR, and quantitative real-time PCR**

Total RNA from maize and teosinte was extracted from frozen tissue using TRIZOL reagent (Invitrogen) and purified on RNeasy columns (Qiagen). Arabidopsis total RNA was extracted from frozen tissue as described previously (Tanimoto et al., 2008). Reverse transcription reactions were performed using the Quanta cDNA Superscript system (Quanta) according to the manufacturer’s instructions. Primer sets used for quantitative real-time PCR (qRT-PCR) are listed in Supplementary Table S2 at JXB online. qRT-PCR was performed with 3–6 independent biological replicates and three technical replicates for each sample. Data were analysed using the 2^−ΔΔCt method as described by Livak and Schmittgen (2001). Expression levels of specific genes were normalized to maize β-tubulin or Arabidopsis glyceraldehyde 3-phosphate dehydrogenase (Supplementary Table S2). Statistical significance between any pair of relative expression means was assessed with a t-test.

**Results**

**Selection of the maize ZCN8 gene for functional testing**

The maize genome contains at least 25 members of the PEBP gene family, encompassing both FT- and TFL-related genes (Danilevskaya et al., 2008). Several lines of evidence suggest that ZCN8 could be the functional equivalent of FT in maize. Although sequence comparisons of ZCN genes with FT and FT-related genes make it difficult to identify any particular ZCN as the clear orthologue of FT, as shown in Fig. 1A, ZCN8 is highly similar to FT and the rice orthologue of FT, Hd3a (74% amino acid identity to both). Moreover, the gene structure of ZCN8 is similar to that of FT and Hd3a (Fig. 1B). A preliminary semi-quantitative PCR analysis by Danilevskaya et al. (2008) and qRT-PCR analysis in this study (data not shown) suggests that ZCN8 is one of only two ZCN genes (the other being ZCN20) that is expressed mainly in leaf tissue, the presumed location where a florigen-encoding gene would be expressed. Therefore, the ZCN8 gene was selected for further analysis.

**ZCN8 expression is highly up-regulated upon floral induction in mature leaves of teosinte**

Teosinte (Z. mays ssp parviglumis) is an obligate SD plant that has an absolute requirement for SD photoperiods to induce flowering (Emerson, 1924). In contrast, in temperate maize, typified by inbred line B73, the transition to flowering occurs after a particular number of leaves are produced. B73 plants with 7–8 visible leaves are at the floral transition stage; that is, the vegetative shoot apex has initiated all leaves, but conversion into an inflorescence meristem has yet to commence (McSteen et al., 2000). For this study, expression of ZCN8 in B73 was analysed at the 8-leaf floral transition stage after growth under SD conditions, the same exposure given to teosinte for photoinduction (Fig. 2A; Supplementary Fig. S1 at JXB online). Growth of teosinte under SD conditions for ≥7 d results in 100% conversion of plants to reproductive growth (data not shown).

For both maize and teosinte, the blade region of leaf 4 and leaf 7 was isolated from each plant to assess expression levels of ZCN8 by qRT-PCR. Only leaf tissue was analysed because ZCN8 transcripts were not detected in immature leaf tissue or shoot apical regions (data not shown). In addition, samples were taken at several time points during the course of a day (2, 6, 10, and 14 h after dawn) to assess the effects of light and dark exposure on ZCN8 expression. As shown in Fig. 2A, ZCN8 leaf transcript levels were much higher under SD conditions compared with LD-grown teosinte plants at all time points, with ZCN8 levels ~10 times higher overall for time points 2, 6, and 10 h, and up to 60–80 times higher at the 14 h time point. Interestingly, SD-grown B73 leaves also showed an increase in ZCN8 transcript levels, but the induction level was much lower than that observed for teosinte (Fig. 2B). Another
interesting observation is that $ZCN8$ expression in teosinte shows greater relative induction at 14 h after dawn (Fig 2A). At this time point plants have been grown in the dark for 5 h, suggesting that $ZCN8$ mRNA may accumulate in the dark. A similar effect was observed in B73 plants, but to a much lesser extent (Fig. 2B). However, the expression differences were much more variable in B73, so it is difficult to assign a pattern to the expression profile.

**$ZCN8$ expression is dependent on $id1$ activity**

Expression of $ZCN8$ in normal (‘WT’) and $id1$ mutant maize leaves was analysed to determine whether the absence of $id1$ activity affected $ZCN8$ transcript accumulation. Loss-of-function $id1$ mutants are indistinguishable from normal maize until the floral transition point (Coneva et al., 2007). In addition, $id1$ transcript accumulation is highest at the floral transition stage; therefore, expression levels in leaves from plants at this stage of development were determined. As shown in Fig. 2C, $ZCN8$ levels in leaves of $id1$ mutants are severely reduced compared with WT plants at the transition stage. The difference in transcription was most dramatic in leaf 7, where WT plants had on average $>15$ times the level of $ZCN8$ RNA. This contrasts with the SD versus LD analysis in B73 (Fig. 2B), where higher expression differences occur in leaf 4 compared with leaf 7 under SD conditions. Overall, these results show that normal $id1$ function in leaves is associated with high levels of $ZCN8$ expression. Analysis of expression in immature leaves and shoot apical regions of $id1$ mutants showed no $ZCN8$ accumulation in these tissues, demonstrating that loss of $id1$ function does not alter the $ZCN8$ expression pattern (data not shown).

**Ectopic overexpression and phloem-specific expression of $ZCN8$ in Arabidopsis causes early flowering and complements the $ft$ mutant phenotype**

Ectopic overexpression via the 35S promoter and phloem companion cell-specific expression via the SUC2 promoter provided evidence that $ZCN8$ encodes a protein that acts as a floral regulator in Arabidopsis. A total of five independent transgenic lines with the 35S::$ZCN8$ construct were selected for flowering time analysis; lines Z2 and Z5 were created by transforming the 35S::$ZCN8$ construct directly into $ft$-1 mutant plants, and X2, Y1 and F3 lines carried the construct in Ler WT plants. For most of these lines, flowering time was shown to be significantly earlier than in WT or $ft$-1 mutant plants under inductive LD conditions average normalized expression in $id1$ leaves is used as a calibrator to generate fold induction in $ZCN8$ expression in WT relative to $id1$ plants. Statistical significance ($P < 0.05$, denoted by an asterisk) of fold difference values is determined by a t-test. Horizontal bars show day/night cycles, and sampling time points are denoted by inverted triangles.
observed when FT is overexpressed by the 35S promoter (Kardailsky et al., 1999; Kobayashi et al., 1999).

Expression of ZCN8 in phloem companion cells also rescued the ft-1 mutation, but did not cause developmental defects (Fig. 4A, D). Ten SUC2::ZCN8 lines in ft-1 mutants were created (Supplementary Table S1 at JXB online); flowering time and leaf number for four lines under LDs are shown in Fig. 3A. Under these conditions, all lines flowered at about the same time and made as many leaves as the WT (~20 d, eight leaves) or were slightly earlier.

Flowering of the overexpressing line Y1 and the two SUC2::ZCN8 lines (C9 and J9) was compared with that of the WT and ft mutants under non-inductive SD conditions (Fig. 3B). As under LD conditions, Y1 flowered extremely early, making fewer than three leaves on average, and showing a terminal flower phenotype in some cases (Fig. 4C). SUC2::ZCN8 lines grown in SDs flowered at about the same time as WT plants grown under inductive LDs (Figs 3A, B, 4D). As was observed with LD growth, SUC2::ZCN8 lines showed no developmental defects. Several transgenic lines were selected for qRT-PCR analysis of expression levels in mature leaves. As can be seen in Fig. 3C, all lines showed expression of the ZCN8 transgene. Unexpectedly, the SUC2::ZCN8 lines showed significantly higher expression than the line Y1, which had one of the strongest phenotypes and showed developments defects. It is possible that ectopic expression of ZCN8 in the shoot apical region has a more dramatic effect than phloem companion cell expression (see Discussion).

Overall, these data show that ectopic expression of ZCN8 in Arabidopsis is able to compensate for the lack of a functional FT gene. Similarly, overexpression under SD conditions simulates growth under inductive LDs, as would be expected for ectopic expression of FT.

Discussion

Long-standing physiological evidence predicted the existence of a mobile, leaf-derived flower-inducing signal, even though the identification and isolation of florigenic compounds turned out to be elusive. It is now widely accepted that Arabidopsis FT protein is a florigen and most, if not all, plants may have orthologous versions of FT that act as mobile flowering signals (Zeevaart, 2008). Here, the ubiquitous presence of FT-related genes that encode florigens is further supported by evidence that maize ZCN8 encodes a putative FT orthologue. This supports other findings that report the presence of FT-like genes in grasses, such as wheat and barley (Yan et al., 2006). Whether ZCN8 encodes the sole florigen in maize is not clear, as there are at least 25 members of the ZCN gene family (Danilevskaya et al., 2008). In rice, the Hd3a gene was the first FT orthologue identified in grasses, and subsequently was shown to migrate from leaf to shoot apex (Kojima et al., 2002; Tamaki et al., 2007). More recently another rice gene with similarity to Hd3a, RFT1, was found to have a role in controlling flowering (Komiya et al., 2008). Therefore,
Fig. 4. Ectopic ZCN8 expression affects flowering in transgenic Arabidopsis. (A) Growth under LD conditions after 24 d. Left to right: ft-1 mutants in the Ler background; SUC2::ZCN8 in ft-1; 35S::ZCN8 in ft-1; wild-type. All plants are in the Ler ecotype background. (B and C) Examples of terminal flower and curling leaf phenotypes typical of 35S::ZCN8 transgenic plants in the Ler and ft-1 background, respectively. Scale bar=0.5 cm. (D) Comparison of flowering of SUC2::ZCN8 transgenic plants (right) with the ft-1 mutant under short-day conditions after 60 d.

Multiple FT orthologues exist in rice. Similarly, the Arabidopsis gene TWIN SISTER OF FT (TSF) was shown to act redundantly with FT in controlling flowering (Yamaguchi et al., 2005; Mathieu et al., 2007; Jang et al., 2009). Given that maize is an allotetraploid resulting from genome duplication (Gaut and Doebley, 1997), the existence of multiple, functional florigen genes would not be unexpected. However, since ZCN8 has the high amino acid sequence similarity to FT (Fig. 1A) and is the only ZCN reported to interact strongly with DLF1 protein so far (Danilevsky et al., 2008), it is a good candidate for a maize florigen. Moreover, the ZCN8 gene maps very close to a strong maize QTL for flowering time on chromosome 8, Vgt2 (Chardon et al., 2005; Coles et al., 2010). The identity of the gene underlying this QTL has not yet been revealed, but ZCN8 would be a viable candidate. The leaf-specific expression of ZCN8 demonstrated here is further proof that ZCN8 encodes a mobile flowering signal.

ZCN8 expression in the leaf is controlled by endogenous flowering signals

Although a florigen was first proposed to mediate flowering in response to photoperiod induction (such as LD-grown Arabidopsis and SD-grown rice), grafting experiments demonstrated that it also has a role in transmitting leaf-derived signals in day-neutral plants (Lang, 1977). Temperate maize exemplified by the B73 inbred used in this study relies almost exclusively on an autonomous mechanism that signals time to flowering after the shoot apex has produced a particular number of leaves. The id1 gene is expressed exclusively in developing leaves; moreover, id1 mRNA and ID1 protein levels do not fluctuate in a diurnal pattern. Therefore, id1 has been proposed to be a regulator of a leaf-derived florigenic signal of the autonomous pathway in maize (Colasanti et al., 1998; Wong and Colasanti, 2007). Transcript levels of ZCN8 are greatly reduced in the leaves of id1 mutants (Fig. 2C), suggesting that ZCN8 relays the flowering signal from an upstream endogenous signal in maize. Analysis of flowering in day-neutral tomato and tobacco species similarly shows that FT orthologues act as a florigen in these species (Lifschitz and Eshed, 2006; Lifschitz et al., 2006). The results presented here extend the role of FT-like florigen genes to a day-neutral monocot species and provide further evidence that FT orthologues act as universal mobile stimuli in all flowering plants.

The finding that id1 acts upstream of ZCN8 supports studies in rice that show that the rice id1 orthologue (RID1, OsId1, or Ehd2) acts upstream of the Hd3a gene (Matsubara et al., 2008; Park et al., 2008; Wu et al., 2008). Therefore, the leaf-specific id1-ZCN8 hierarchy appears to be conserved in maize and rice, which are both grasses of
tropical origin. However, other elements are not conserved, such as the rice Early heading day 1 (Ehd1) gene, a B-type response regulator that also acts upstream of Hd3a and is a component of the SD photoperiod pathway (Doi et al., 2004). No Ehd1 orthologue has been reported in maize; therefore, Ehd1 may represent an activator of Hd3a expression that is unique to rice. It has been proposed that the rice id1 orthologue is a master regulator of both photoperiod and autonomous pathways (Wu et al., 2008). Whether maize id1 controls both photoperiod and autonomous pathways seems unlikely since studies show no diurnal fluctuation of id1 expression and no induction of id1 in photoperiod-induced teosinte (Coneva et al., 2007; Wong and Colasanti, 2007).

ZCN8 integrates both endogenous and photoperiod signals

Overall the findings presented here suggest that ZCN8 integrates signals from both the photoperiod and autonomous pathways in maize. A simple model is shown in Fig. 5A, where floral-inductive, leaf-derived signals impinge on ZCN8 from an autonomous pathway, mediated by id1 activity, and from signals activated by the inductive SD photoperiod. In this proposed model, ZCN8 is a checkpoint that can assimilate different inductive signals. Whether id1 has a role in mediating the floral transition in teosinte or other tropical maize that requires SD photoperiods to induce flowering is unknown. Nevertheless, this study suggests that the evolution of day-neutral maize from a tropical ancestor retained the function of ZCN8 as an integrator of inductive signals, whether they are environmental or autonomous.

Phloem-specific expression and overexpression of ZCN8 rescues the Arabidopsis ft-1 mutant and causes extreme early flowering

Ectopic expression of ZCN8 in transgenic Arabidopsis plants provides further proof that ZCN8 has the properties of a universal, leaf-derived florigen. Initial studies in Arabidopsis found that overexpression of FT driven by the 35S promoter rescued the ft mutation and also caused extremely early flowering (Kardailsky et al., 1999; Kobayashi et al., 1999), as did overexpression of the TSF gene (Yamaguchi et al., 2005). In addition to early flowering, these studies report developmental anomalies in 35S::FT plants similar to what is found in the current study (i.e. terminal flower formation and curling of the first few leaves). Therefore, ZCN8 overexpression has the same effect as overexpression of the FT gene in Arabidopsis; but most importantly has the ability to complement the ft mutation. Later experiments showed that FT expression under the control of the phloem companion cell-specific SUC2 promoter could also rescue the ft mutation (Jaeger and Wigge, 2007; Mathieu et al., 2007). In this study, the finding that the SUC2::ZCN8 transgene complements ft in Arabidopsis (Figs. 3A, 4) demonstrates an important point; namely, that maize ZCN8 synthesized in phloem cells is able to activate floral transition at the shoot apex. Similar to what is observed for Arabidopsis FT and rice Hd3a proteins, it is likely that ZCN8 acts as a florigen and moves to the shoot apex to mediate the transition. However, it is possible that ZCN8 causes the production of a secondary florigenic signal in the leaf and that this component migrates to the apex. Further studies would be required to show definitively that ZCN8 is a mobile signal. Nevertheless, the data presented here provide strong evidence that ZCN8 has properties of a florigen. The observation that most SUC2::ZCN8 transgenic lines flower at the same time as or only slightly earlier than WT plants suggests that phloem-specific expression does not cause developmental abnormalities associated with ectopic overexpression. Interestingly, this was supported by the finding that expression levels of ZCN8 in leaves were often found to be higher that in the 35S lines (Fig. 3C). This may suggest that phloem-specific expression has an intrinsic ‘gating’ mechanism that regulates the level of ZCN8 (or FT) protein that migrates to the shoot apex.

Does id1 act as an autonomous activator of ZCN8 expression in temperate maize?

The nature of the upstream mechanism that controls ZCN8 expression in the leaf remains an open question. In Arabidopsis, the role of the CONSTANS gene (CO) as a sensor of photoperiod signals via the circadian clock and the direct activation of FT expression in leaves is well established (reviewed in Turck et al., 2008). In maize, the conz1 gene, a homologue of Arabidopsis CO, was shown to exhibit a diurnal expression pattern, suggesting a possible role in photoperiod control of flowering (Miller et al., 2008). However the role of conz1 in flowering time control has not been reported, and whether CONZ is an activator of ZCN8 needs to be investigated. It will be interesting to ascertain whether teosinte and tropical maize, which depend on SD photoperiods to flower, contain a functional CO orthologue that activates ZCN8 expression. In maize, even less is known about the mechanisms underlying endogenous flowering signals. The finding that absence of id1 activity reduces ZCN8 expression suggests that an ID1–ZCN8 regulatory module may exist in day-neutral maize leaves, similar to the CO–FT module in Arabidopsis and the Hd1–Hd3a module in rice. It is of interest to note that the temporal and spatial expression patterns of id1 and ZCN8 do not overlap; that is, id1 activity is confined to the immature, non-photosynthetic part of developing leaves (Colasanti et al., 1998; Wong and Colasanti, 2007), whereas ZCN8 expression is localized to mature leaves (Fig. 5B). Therefore, it is unlikely that ZCN8 is a direct target of the ID1 transcriptional regulator in the way that FT is a direct target of CO (Samach et al., 2000). One possibility is that ID1 acts in the basal portion of the leaf to regulate the production of an unidentified mobile signal that moves to the mature, green portion of the leaf to activate ZCN8 expression. Given that activation is indirect in this scenario, numerous intermediary factors may exist to control ZCN8 expression (Fig. 5A). An alternative possibility
is that ID1 functions in early stages of leaf development to generate a mature leaf that is competent to produce florigenic signals, including expression of ZCN8. This latter scenario is intriguing in that it suggests an epigenetic role for id1 in patterning the mature leaf expression profile. Increasing evidence from studies of vernalization and autonomous pathways in Arabidopsis suggest that epigenetic mechanisms, such as RNA-mediated DNA methylation and establishment of chromatin states, are central components of flowering control (reviewed in He, 2009; Amasino, 2010). Further, recent studies show that FT and TSF expression is subject to epigenetic control through specific chromatin modifications (Adrian et al., 2010; Yang et al., 2010). Preliminary evidence that ID1 protein interacts with proteins that have putative roles in mediating RNA-directed DNA methylation and chromatin modification support this idea (M. Tanimoto, R. Hilborn, A. Kozaki and J. Colasanti, unpublished). It will be of interest to determine whether epigenetic programming during leaf development is the basis of autonomous regulation of leaf competence to produce florigen.

Supplementary data

Supplementary data are available at JXB online. Figure S1. Quantitative RT-PCR analysis of ZCN8 expression in leaf 4 and leaf 7 of teosinte and B73 maize plants at the V8 stage.

Table S1. Days to flowering and total leaf number at flowering for all 35S::ZCN8 and SUC2::ZCN8 transgenic constructs in Arabidopsis under long-day and short-day growth conditions.

Table S2. Primers used for qRT-PCR and gene cloning.

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