Running head
Dynamic activities of plant microRNAs

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Updates
The regulatory activities of plant microRNAs: a more dynamic perspective

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ABSTRACT

Twenty years have passed since the first discovery of the microRNA (miRNA) genes in *Caenorhabditis elegans*. Based on the growing research progress, we are approaching an understanding of this small RNA species, which seemed to be mysterious before. The regulatory activities of miRNAs have been extensively studied through target identification, physiological and phenotypic assays by using bioinformatic, genetic, and biochemical approaches. However, recent evidences indicate that the effective levels of miRNAs are determined by transcription, processing, miRISC (microRNA-induced silencing complex) loading, action, turnover use, and decay. Each process is affected by certain factors, such as genomic modifications, RNA editing, miRISC loading competition, target abundance and complementarity, and spatio-temporal effects, thus conferring a highly dynamic feature to the miRNA activities. To maintain the steady-state levels of the functional miRNAs, thus ensuring normal physiological and biochemical status, plants employ several exquisite strategies, such as feedback regulation and buffering system, to minimize the influence of external signal fluctuations. In this review, we raised the notion that a more dynamic picture of miRNA activities should be drawn to construct comprehensive miRNA-mediated networks in plants.

INTRODUCTION

MicroRNAs, ~21 nucleotides (nt) in length, were identified as a small RNA (sRNA) species with essential regulatory roles in various biological processes (Carrington and Ambros, 2003). The transcription of most miRNA genes is guided by RNA polymerase (Pol) II (Lee et al., 2004; Xie et al., 2005). Following the transcription, the single-stranded RNAs with internal stem-loop structures are then recognized by Drosha and Dicer in animals (Kim et al., 2009) or Dicer-like 1 (DCL1) in plants (Voinnet, 2009) for sequential cleavages, converting the pri-miRNAs (primary microRNAs) to the pre-miRNAs (precursor microRNAs), and finally to the miRNA/miRNA* duplexes. After dissociation from the duplexes, the miRNAs are incorporated into Argonaute (AGO)-associated miRISCs (preferentially AGO1-associated miRISCs). Although the sophisticated model of miRNA biogenesis is seemingly settled for each step, there exist many key nodes that influence the final activity of a miRNA gene. The transcription of miRNA genes is under rigorous surveillance of many *cis*- and *trans*-factors, such as chromatin marks and specific transcription factors (TFs). The processing efficiency of the miRNA precursors is
basically determined by the sequences and the structures of their own, and is regulated in a spatio-temporal manner (Davis and Hata, 2009; Cuperus et al., 2011; Zhu et al., 2011). Furthermore, sorting of miRNAs into specific AGO complexes should not be oversimplified, since not all the miRNAs are uniformly loaded into AGO1-associated miRISCs. More complicadly, loading competition between miRNAs and other sRNAs occurs in planta.

In plants, miRNAs guide the miRISCs to the target transcripts containing highly complementary recognition sites to exert their repressive role on gene expression. This seemingly simple one-to-one regulation occurs with several concomitant events, which strongly affect the regulatory intensity. For instance, the degradation rate of a miRNA was reported to be highly dependent on the target abundance and complementarity (Chatterjee and Grosshans, 2009; Ameres et al., 2010; Arvey et al., 2010). After one cleavage of a specific target, the miRISC may survive, or the released miRNA could form another miRISC, both of which will involve in another round of targeting. This turnover rate is also determined by the target complementarity. Quite different scene exists between miRNAs and their low-complementary targets. For the miRNAs sequestered by the bulge targets, their turnover rate is intensively reduced.

All the evidences point to the conclusion that the regulatory activities of the miRNAs are highly dynamic. From transcription, to precursor processing, to miRISC loading, then to target recognition and miRNA-mediated regulation, and finally to miRNA degradation and turnover, numerous crucial factors hide behind the apparently steady-state levels of the mature miRNAs. From another point of view, the miRNA-mediated regulation itself is strictly regulated in many aspects, making the miRNA-involved networks more robust. Based on the recent research progresses, we raised the opinion that a dynamic view should be provided to measure the miRNA activities more precisely in plants.

TRANSCRIPTIONAL CONTROL OF MIRNA GENES
Increasing evidences point to the fact that the accumulation of a specific miRNA is a combinatory effect of its transcription, processing, and degradation (Kai and Pasquinelli, 2010). As the first step of miRNA expression, their transcription is modulated in a highly dynamic manner. Both cis-modifications and trans-acting factors are responsible for the spatio-temporally restricted expression patterns of miRNA genes (Chen, 2009; Davis and Hata, 2009; Winter et al., 2009) (Figure 1A).

One major form of the cis-regulation is known as chromatin modifications, including DNA methylation and histone modifications. Such kind of epigenetic marks can be present within the upstream or downstream regions, or the bodies of the miRNA genes, which are extraordinarily variable according to the cellular contents and environmental stimuli. These marks have shown great potential in influencing the transcriptional status of miRNA genes. As proposed by Rodriguez-Enriquez et al. (2011), somaclonal variation, a featured phenomenon observed in plant tissue culture, is one of the biological consequences caused by miRNA misexpression and the accompanied disordered regulatory pathways. In their hypothesis, the inducers introduced by in vitro tissue culture could result in aberrant miRNA transcription, processing and miRISC loading, which could have remarkable impact on the transcriptome and the proteome, and further alter the epigenetic status of the genome in cultured cells. In turn, the miRNA transcription could be influenced by the altered epigenetic marks surrounding the miRNA genes (Rodriguez-Enriquez et al., 2011). Another example was provided by Kim et al. (2009) recently. A histone acetyltransferase, GCN5 (general control non-repressed protein 5), was indicated to interfere miRNA biogenesis transcriptionally and post-transcriptionally. The GCN5-mediated histone modifications serve as an epigenetic mechanism for modulating miRNA production (Kim et al., 2009).

The transcription of most miRNA genes is mediated by RNA Pol II (Lee et al., 2004; Xie et al., 2005). And, the structures of the miRNA promoters are similar to those of the protein-coding genes (Megraw et al., 2006; Zhou et al., 2007). For example, the distribution patterns of the basic cis-elements for transcriptional control, i.e. the TSS (transcription start site), the TATA-box, and the CAAT-box, on the
miRNA promoters were demonstrated to be identical to the protein-coding genes (Meng et al., 2009). In plants, many TFs have been identified as trans-acting factors with roles in transcriptional modulation of certain miRNA genes. One example is the PHR1 (PHOSPHATE STARVATION RESPONSE 1)—miR399—PHO2 (defined by the mutant pho2) regulatory pathway involved in phosphorous homeostasis (Bari et al., 2006). Upon phosphorous deprivation, miR399 is upregulated transcriptionally by the activated PHR1, a direct upstream regulator. Then, the repression of PHO2 by miR399 is subsequently reinforced post-transcriptionally. This cascade ensures the expeditious response of the plants under phosphorous-deficient condition, enabling more efficient use of both environmental and cellular resources of phosphorus. Intriguingly, some TFs were also targeted by the downstream miRNAs, forming feedback circuits in certain signaling pathways. For instance, within the auxin signaling pathway implicated in Arabidopsis (Arabidopsis thaliana) adventitious root development (Gutierrez et al., 2009), miR160 is transcriptionally regulated by ARF6 (AUXIN RESPONSE FACTOR 6) and ARF17, and miR167 regulated by ARF6, ARF8, and ARF17, respectively. On the other hand, all the three ARF genes are negatively regulated by either of the two miRNAs. These feedback circuits form a quite interlaced network that could decipher, integrate, and transduce the light and the auxin signals to shape normal root system architecture. Another exquisite case was presented by Wu and colleagues (2009). Both miR156 and miR172 were demonstrated to participate in the regulatory network that was essential for developmental timing in Arabidopsis. These two miRNAs act by repressing the expression of TFs belonging to SPL (SQUAMOSA PROMOTER BINDING PROTEIN LIKE) and AP2-like (APETALA2-LIKE) gene families, respectively. Certain members of the two TF families were proved to regulate miR156 and miR172 positively, thus forming negative feedback loops that contributed to the normal juvenile-to-adult phase transition. More complicatedly, the transcription of miR172 was directly regulated by SPL9 and SPL10, which were both targeted by miR156. These connections established the miR156—SPL—miR172—AP2 regulatory cascade, which was crucial for vegetative phase change of Arabidopsis (Wu et al., 2009). However, all these
findings only uncovered a tip of the iceberg of miRNA- and TF-involved networks. The one-to-one and multiple-to-one regulatory relationships between TFs and specific miRNA genes should not be at a stationary state. Instead, they are highly dynamic due to numerous intrinsic factors, such as spatio-temporal expression of TF genes and indirect TF—miRNA regulation. Facilitated by the technical advances, a more comprehensive view of such networks could be constructed through genome-wide identification of TF binding sites (Macquarrie et al., 2011).

Expression pattern analyses of plant miRNAs by high-throughput profiling or fine-scale quantification revealed that numerous miRNAs were expressed in a tissue- or stage-specific manner, and dozens of miRNAs could be induced by external stimuli (Reinhart et al., 2002; Kidner and Martienssen, 2004; Sunkar and Zhu, 2004; Lu et al., 2005; Yao et al., 2007; Liu et al., 2008b; Oh et al., 2008; Hsieh et al., 2009; Johnson et al., 2009; Simon et al., 2009). All these evidences indicate that the miRNA activities are highly variable at distinct developmental stages, upon diverse treatments, or in different tissues. Conceivably, the strict control of miRNA expression at both chromatic and transcriptional levels could make great contribution to the highly dynamic nature.

**PROCESSING AND MATURATION, CRUCIAL STEPS FOR MIRNA BIOGENESIS**

After transcription, the primary products, i.e. pri-miRNAs, will be subjected to DCL1-mediated two-step cleavages in the nucleus in plants (Papp et al., 2003; Kurihara and Watanabe, 2004). Several aspects should be taken into account to assess the dynamic efficiency of the miRNA precursor processing. One of the well-characterized models balancing processing and miRNA activities is the feedback circuit formed between \( \text{DCL1} \) and \( \text{miR162} \) (Xie et al., 2003). The nuclear-localized DCL1 with RNase III activity is indispensable for the processing of most plant miRNAs (Voisinnet, 2009). Thus, the levels of the final products of the miRNA genes, i.e. the mature miRNAs, are highly correlated to the expression of \( \text{DCL1} \). On the other
hand, DCL1 itself is regulated by miR162 post-transcriptionally to avoid plethoric DCL1 activity (Xie et al., 2003). Moreover, the tissue-specific regulation of miRNA processing by DCLs was proposed recently. The over-accumulated level of DCL3 in specific tissue may result in a shift of the substrates of DCL1 to the DCL3’s (Vazquez et al., 2008). Similar substrate competition may also occur between DCL1 and other DCLs.

In addition, different miRNA precursors possess different affinities to DCL1 due to distinct sequence characteristics and spatio-temporal distributions. Although the precursor sequences are largely determined by the genomic sequences of the miRNA genes, several pieces of evidence in animals show that RNA editing mediated by ADAR (ADENOSINE DEAMINASE ACTING ON RNA) can occur on the mature miRNAs or the precursors post-transcriptionally, which has remarkable effects on miRNA processing and targeting (Luciano et al., 2004; Blow et al., 2006; Yang et al., 2006b; Kawahara et al., 2007; Kawahara et al., 2007; Kawahara et al., 2008; Winter et al., 2009; Krol et al., 2010). Different from animals, RNA editing in plants, mostly represented by C-to-U base conversion, is carried out by PPR (PENTATRICOPEPTIDE REPEAT) family proteins (Schmitz-Linneweber and Small, 2008), and is restricted to plant organelles including mitochondria and plastids based on available reports (Shikanai, 2006). Recent bioinformatic analyses by using huge high-throughput sequencing (HTS) data sets raised the possibility that RNA editing of miRNA gene products could also take place in plants (Ebhardt et al., 2009; Iida et al., 2009; Meng et al., 2010a). Once further experimental validations are available, this kind of sequence modifications could be another dynamic layer underlying miRNA processing, maturation and action.

Depending on the in vitro levels and the structures, miRNA precursors, perhaps along with other sRNA precursors, could compete for the machineries functioning in the miRNA biogenesis pathway. One such competition in plants could be raised by different miRNA precursors and other stem-loop-structured precursors for the accessibility to DCL1 or other DCLs such as DCL3, which has been mentioned above (Vazquez et al., 2008). In animals, manually introduced short hairpin RNAs could
interfere with the expression of endogenous miRNA genes through drastic competition for the nuclear exportation and processing machineries (Grimm et al., 2006; Stewart et al., 2008).

In mouse, post-transcriptional regulation was found to reside within the miRNA processing procedure. During early developmental stage or in mouse primary tumors, many miRNA precursors were highly accumulated while their processing was intensively blocked (Thomson et al., 2006). It suggests that the expression of miRNA genes could be spatio-temporally modulated at post-transcriptional level. Although it needs further verification, this strategy is likely to be employed by the plant miRNA biogenesis system. Besides, several reports in animals point to the fact that AGO proteins participate in miRNA processing (Diederichs and Haber, 2007; O’Carroll et al., 2007; Cheloufi et al., 2010; Cifuentes et al., 2010; Lund et al., 2011). However, to our best knowledge, there has been no such finding in plants yet. The only related study reported that AGO1 was involved in the stabilization of certain miRNAs (Vaucheret et al., 2004; Vaucheret et al., 2006). That is, AGO1 is highly correlated with the degradation rate of the mature miRNAs. If AGO1 indeed acts on the miRNA processing in plants, its spatio-temporal distribution pattern could contribute to the tissue- or stage-specific expression of many miRNA genes.

Recent study carried out by Hoffer et al. (2011) discovered that post-transcriptional gene silencing (PTGS) guided by siRNAs (small interfering RNAs) could take place in the nucleus in plants, which has revolutionized the traditional view that the targets of PTGS are mature mRNAs (messenger RNAs) or other transcripts in cytoplasm. On the other hand, Mortensen and colleagues (2011) showed that in *Xenopus laevis* oocytes, siRNAs antisense to the miRNA precursors were able to deplete the generation of the mature miRNAs. Since the pri-miRNAs and the pre-miRNAs are both nuclear-localized in the plant cells, it is reasonable to imagine that certain siRNAs, either intrinsic or extrinsic, may be capable of controlling the cellular levels of specific miRNA precursors. Furthermore, we previously proposed a feedback model between miRNA(*)s and the parental precursors that the miRNA(*)s could bind to the complementary sites on their precursors to exert a cleavage-based
repressive role, thus modulating the biogenesis of themselves. Thus, it provides another regulatory layer of miRNA transcripts (Meng et al., 2010b). It is worth mentioning here that recent evidences in animals showed a great potential of miRNA precursors in target recognition and repression (Trujillo et al., 2010). And, the loop sequences of the precursors could determine the activities of the corresponding mature miRNAs directly (Liu et al., 2008a). If these are also true in plants, an interlaced connection between miRNA processing and action could be established.

The exosome, responsible for 3’-to-5’ RNA processing and degradation, is critical for RNA metabolism in organisms (Mitchell et al., 1997). A transcriptome-wide high-resolution mapping was applied by Chekanova et al. (2007) to exhaustively identify the exosome substrates in Arabidopsis. Intriguingly, miRNA processing intermediates were cloned as one kind of exosome substrates. Since numerous exosome targets have been identified in nucleus (Bousquet-Antonelli et al., 2000; Torchet et al., 2002; Das et al., 2003; Kadaba et al., 2004; Kadaba et al., 2006), it is reasonable that the nuclear-localized processing intermediates of plant miRNA precursors are under tight surveillance by the exosomes. Based on this result, the authors proposed that exosome-mediated degradation of these processing intermediates could facilitate efficient recycling of the miRNA processing machineries (Chekanova et al., 2007). Moreover, the RRP6 exosome subunit in Chlamydomonas reinhardtii possesses a quality control role in eliminating dysfunctional or damaged sRNA molecules including mature miRNAs and siRNAs (Ibrahim et al., 2010). From this point of view, the exosome could be another important factor affecting the efficiency of miRNA processing in plants.

After DCL1-mediated two-step cleavages, the miRNA/miRNA* duplexes will be recognized by HEN1 (HUA ENHANCER 1) to add methyl groups on the 2’ OH of the 3’-most terminal nucleotides on both strands (Yu et al., 2005). This is another crucial step for miRNA maturation, since terminal methylation could protect them from 3’-end uridylation and adenylation, thus stabilizing the miRNAs and the miRNA*s in vivo (Li et al., 2005; Yang et al., 2006c). Interestingly, HEN1 is not specific to miRNA duplexes. The study by Yang et al. (2006c) showed that both
miRNA/miRNA* and siRNA duplexes ranging from 21 to 24 bp (base pairs) could be methylated. Besides, a recent study by Yu et al. (2010) further validated the competition between siRNAs and miRNAs for HEN1-mediated methylation. In this regard, the methylation-based stabilization that relies on both HEN1 activity and substrate levels could contribute to the varying abundances of the effective miRNAs.

Taken together, processing and maturation are two speed-limiting steps for the final miRNA levels (Figure 1B). In both plants and animals, there are enormous factors and several check points modulating these susceptible steps (Davis and Hata, 2009; Voinnet, 2009; Winter et al., 2009), which confer a highly dynamic nature to the miRNA activities.

**RISC SORTING, WITH A DOMINANT BUT NOT COMPLETELY DETERMINED LOADING PATTERN**

To exert their regulatory roles, the mature miRNAs released from the miRNA/miRNA* duplexes must be subsequently sorted into AGO-associated miRISCs (Voinnet, 2009). Two components of the sRNA sequence characteristics, i.e. 5’ terminal composition and sequence length, were demonstrated to be the key determinants for their AGO sorting patterns (Kim, 2008; Mi et al., 2008; Montgomery et al., 2008; Ebhardt et al., 2010). By employing the HTS technology to investigate the sRNA contents within the immunopurified AGO complexes, Qi’s group (2008) observed that the sRNAs started with 5’ A (adenosine) were preferentially recruited by AGO2 and AGO4, and those initiated with 5’ C (cytosine) were loaded into AGO5-associated silencing complex. For the miRNAs, most of which favored 5’ U (uridine), were largely incorporated into AGO1 complex. Additionally, AGO1- and AGO2-associated sRNAs were predominantly 21 nt in length, and AGO4-associated ones tended to be 24 nt, indicating a critical role of sequence length in AGO sorting (Mi et al., 2008). However, these two factors are not sufficient to determine which AGO(s) should a specific sRNA associate with. In Mi et al.’s study (2008), AGO5 was demonstrated to bind the sRNAs belonging to three size classes, i.e. 21, 22 and
Moreover, recent result revealed the association between AGO10 and miR166/165, which can not be explained by the 5’ composition- and sequence length-based rule (Zhu et al., 2011). Another exceptional case that miR390 interacts with AGO7 for subsequent ta-siRNA (trans-acting small interfering RNA) production suggests that the miRNA species are not always associated with AGO1. The 5’ A of miR390 was suggested to specifically determine the preferential association of miR390 with AGO7 but not AGO1 (Montgomery et al., 2008). In the well-established model of miRNA biogenesis, the strand with less stably paired 5’ end of a specific duplex is selectively recognized as the guide strand and loaded into AGO1-associated complexes (Jones-Rhoades et al., 2006). From this point of view, other sequence- or structure-based features embedded within the miRNA/miRNA* duplexes could play an important role in determining the destination of the miRNAs.

Notably, several dynamic factors should not be excluded when we try to interrogate the association between a certain AGO protein and a miRNA, considering that unexpectedly drastic loading competition might take place in a specific cellular context (Figure 1C). Two distinct layers exist in this kind of competition: two or more AGOs compete for one miRNA, and miRNA, miRNA*s and other sRNAs strive to incorporate into a specific AGO complex. A specific example was provided by Zhu et al. (2011) on the loading balance of miR166/165 between AGO1 and AGO10 in Arabidopsis. miR166/165 occupied a dominant portion of the AGO10-bound miRNAs, and the featured structure of miR166/miR166* duplex predetermined the preferential association of miR166 with AGO10 (Zhu et al., 2011). This result well supports the structure-based rule for miRNA sorting as proposed above. More interestingly, loss-of-function mutation of AGO10 significantly enhanced the association of miR166 with AGO1. Considering the elucidated role of AGO10 in maintaining undifferentiated cell state of the shoot apical meristems (SAM) (Moussian et al., 1998; Lynn et al., 1999), the authors proposed that AGO10 competed with AGO1 to sequester miR166/165, thus preventing them from targeting HD-ZIP III genes involved in SAM maintenance (Prigge et al., 2005; Barton, 2010; Zhu et al., 2011). Considering the partially overlapping roles of some AGO family members
within the plant sRNA pathways (Vaucheret, 2008; Mallory et al., 2009; Mallory and Vaucheret, 2010), we suggest that this kind of loading competition, i.e. one miRNA versus multiple AGOs, could be widespread in plants.

In several types of human cells, one investigation carried out by Khan and colleagues (2009) showed that transfected siRNAs could compete with endogenous miRNAs at several points of the miRNA biogenesis pathway, such as nuclear exportation and miRISC loading. It was observed that many targets of the endogenous miRNAs were significantly upregulated after siRNA transfection, which exhibited concentration and temporal dependence. The authors proposed that the intracellular machineries for miRNA processing and action could be saturated through the invasion of sRNAs sharing overlapping biogenesis pathways with the miRNAs, and they could also compete with the miRNAs for target binding (Khan et al., 2009). In this regard, it is possible that competition among two or more sRNA species for nuclear exportation, RISC loading, and target binding may occur in plants. This scenario is reasonable considering the notion that several indistinguishable intersections exist within the biogenesis and functioning pathways between the young miRNA genes and the siRNAs in plants (Cuperus et al., 2011). Besides, the miRNA*s were recently reported to possess regulatory roles in both animals (Okamura et al., 2008; Packer et al., 2008; Yang et al., 2011) and plants (Mi et al., 2008; Devers et al., 2011; Meng et al., 2011; Zhang et al., 2011), which points to the possibility that the miRNA*s are likely to participate in the RISC loading competition (Figure 1C).

In plants, the functional diversification of the AGO proteins is not only attributed to the protein sequences themselves, but is also highly dependent on their spatio-temporal expression patterns (Vaucheret, 2008; Mallory and Vaucheret, 2010; Zhu et al., 2011). Thus, the identical subcellular localizations are the prerequisite for the in vivo association between a specific miRNA and an AGO-associated RISC (Havecker et al., 2010).

A HIGHLY DYNAMIC MIRNA-MEDIATED REGULATORY
SYSTEM IN PLANTS

miRNA turnover

Although increasing evidences point to the fact that translational repression could be adopted as one action mode by the plant miRNAs (Chen, 2004; Gandikota et al., 2007; Brodersen et al., 2008; Dugas and Bartel, 2008; Todesco et al., 2010), most highly conserved miRNAs exert their regulatory roles at post-transcriptional level through cleavages (Jones-Rhoades et al., 2006; Voinnet, 2009). In contrast to the low complementarity between miRNAs and their targets in animals (Carthew and Sontheimer, 2009), the plant miRNA-mediated target slicing largely depends on the near-perfect binding sites resided within the corresponding transcripts (Mallory et al., 2004).

We must recognize that this kind of regulation is not performed in a steady-state mode, but should be highly dynamic. The pressing issue that needs to be addressed is how to assess the regulatory activity of a specific miRNA. Besides the check points resided within the transcription, the processing, and the miRISC loading steps, the spatio-temporal expression patterns of both miRNAs and their targets should be taken into account. However, here, we would like to introduce another notable layer, the turnover use of the mature miRNAs, since less attention has been paid to the fate of the miRNAs subsequent to their first round of target cleavages.

The multiple-turnover model was first raised by Zamore’s group (2002) during the study on the let-7-guided RNA cleavages in human cells. The result showed that each let-7-programmed RISC was capable of catalyzing approximately ten rounds of cleavage action on a specific target (Hutvagner and Zamore, 2002). Also in mammalian cells, another pioneer work was done by Baccarini and colleagues (2011) recently. Quantitative analysis of miR-223 showed that each miRNA molecule could regulate at least two target transcripts during its life cycle. Then, they demonstrated that the miRNA-mediated non-slicing pathway was multiple-turnover (Baccarini et al., 2011). Although this kind of kinetic regulation was unraveled by analyzing only a few miRNAs, and it still needs to verify whether a similar kinetic model could be applied...
to most miRNAs in animals (Muers, 2011), it is tempting for the plant biologists to test the possibility that the recycling strategy is also adopted by plant sRNAs for PTGS (Figure 2A). Once the scenario that miRNAs can be reused is confirmed in plants, our current understanding on miRNA activities will be significantly updated. The turnover use of a specific miRNA molecule could remarkably elevate the targeting efficiency in planta, enabling a strict surveillance of a large pool of target transcripts by a relatively small population of miRNAs. However, this does not mean an invariable one-to-multiple regulation mode. The fluctuant turnover rate of a specific miRNA in different cellular contexts or under diverse conditions predetermines the highly dynamic nature of miRNA recycling. From another point of view, the adjustable turnover rate greatly enhances the buffering capacity of miRNA-involved regulatory system when suffering expression fluctuation of certain target genes. This buffering system ensures the physiologically normal expression of the genes (Figure 2B).

Different from the scene provided by Baccarini et al. (2011) that miRNAs were not irreversibly sequestered by the targets in animals, one piece of evidence in Arabidopsis showed that miR399 was sequestered by a spurious target encoded by the non-coding gene IPS1 (INDUCED BY PHOSPHATE STARVATION 1) (Franco-Zorrilla et al., 2007). Within the miR399—IPS1 binding region, the high complementarity is interrupted by a 3-nt bulge at the expected cleavage site. It leads to an inhibitory effect on miR399 by the non-cleavable IPS1 transcript, and this phenomenon was termed as “target mimicry”. Recently, a large collection of target mimics against dozens of miRNAs were generated to facilitate further functional studies on plant miRNAs (Todesco et al., 2010). The activities of many designated miRNAs were confirmed to be successfully repressed by artificial target mimics, and the abundances of the corresponding targets were observed to be elevated. Hence, target mimicry, or some other similar mechanisms, may provide another control layer of the miRNA turnover rate in planta (Figure 2C).
Silencing amplification

In addition to the miRNA-guided primary regulation, amplification of the silencing signals through secondary siRNA proliferation should be considered when evaluating the plant miRNA activities (Figure 2A). One piece of evidence supporting such activity of miRNAs is their involvement in ta-siRNA generation (Allen and Howell, 2010). To date, four TAS (trans-acting siRNA) gene families, TAS1, TAS2, TAS3, and TAS4, have been discovered to encode ta-siRNAs in Arabidopsis. To enter the RDR6 (RNA-dependent RNA polymerase 6)—DCL4-dependent pathway for ta-siRNA generation (Peragine et al., 2004; Vazquez et al., 2004; Yoshikawa et al., 2005), the primary TAS transcripts should be cleaved by miR173-, miR390-, or miR828-programmed AGO complexes firstly (Allen et al., 2005; Axtell et al., 2006; Rajagopalan et al., 2006; Chen et al., 2007; Montgomery et al., 2008). Another specific example was provided by Carrington’s group (2010). Certain miRNAs associated with AGO1-containing silencing complexes were found to be competent to trigger secondary siRNAs from the target transcripts. This RDR6-dependent pathway is specifically mediated by the 22-nt miRNA species, but not the 21-nt ones (Cuperus et al., 2010). Besides, cleavages of the PPR transcripts by several miRNAs and ta-siRNAs could activate the biogenesis of the PPR-derived secondary siRNAs, which could in turn target the host transcripts in cis or the other homologous genes in trans, reinforcing the miRNA- or ta-siRNA-mediated gene silencing in Arabidopsis (Axtell et al., 2006; Chen et al., 2007; Howell et al., 2007; Addo-Quaye et al., 2008). More recently, the 22-nt-long miR393 was shown to be involved in auxin signal-mediated leaf development through cleavages of the TAAR (TIR1/AFB2 Auxin Receptor) transcripts. Interestingly, the production of the TAAR-derived secondary siRNAs could be initiated by the miR393-guided cleavages, which further enhanced the repressive regulation of the TAAR-related or other homologous genes (Si-Ammour et al., 2011). Furthermore, the study by Chen et al. (2010) also supports the 22-nt model that the secondary siRNA triggers tend to be the miRNAs and the siRNAs of 22 nt, rather than the 21-nt ones.
**Action mode conversion**

Besides the two action modes, i.e. transcript cleavage and translational repression, which are employed by plant miRNAs for target regulation, a miRNA-mediated pathway has been shown to be implicated in DNA methylation (Chellappan et al., 2010; Wu et al., 2010; Chen et al., 2011). Interestingly, in *Physcomitrella patens*, the miRNA-guided mRNA slicing could be converted to another action mode, DNA methylation, which was conditionally dependent on the ratio of a miRNA to its target(s) (Khraiwesh et al., 2010). Thus, the dosage-dependent action mode conversion displays another dynamic layer of miRNA-mediated regulation in plants.

**Subcellular localization**

The canonical model of miRNA-mediated regulation indicates that miRNAs recognize their targets mostly in the cytoplasm after their nuclear exportation and maturation (Carthew and Sontheimer, 2009; Voinnet, 2009). However, current evidences uncovered the novel nuclear-localized expression patterns of mature miRNAs in both plants and animals (Politz et al., 2006; Politz et al., 2009; Wong et al., 2011). More specifically in human beings, Hwang et al. (2007) discovered a hexanucleotide *cis*-element resided within miR-29b, which could direct nuclear import of the examined miRNAs and siRNAs. Based on this result, the authors proposed that the seemingly redundant miRNAs with identical 5’ seed regions could be functionally diversified under the influence of certain *cis*-motifs, such as the 3’ transferable nuclear localization motif (Hwang et al., 2007). To date, only a few cases of the nuclear-localized miRNAs have been discovered, but the variable subcellular localizations point to the possibility that miRNAs could target the nuclear transcripts such as the primary gene transcripts and the miRNA precursors in plants.

**miRNA diffusion**

The dynamic nature of miRNA-mediated regulation in plants is also strongly
reflected by their diffusion effect (Figure 1C). The sRNA molecules including certain miRNAs and siRNAs could not only perform cell-to-cell movement, but also are implicated in long-distance transport through the phloem (Yoo et al., 2004; Kehr and Buhtz, 2008; Brosnan and Voinnet, 2011), which were demonstrated to serve as systemic signals for leaf development (Juarez et al., 2004) and phosphate homeostasis (Pant et al., 2008). From this point of view, in many cases, the plant miRNAs could exert non-cell-autonomous control over plant growth and development through cell-to-cell, tissue-to-tissue, or even organ-to-organ communications. Henceforth, we should not restrict the miRNA-mediated regulation within a limited context, since the diffusion effect must be treated as an important factor when assessing the miRNA activities.

**Regulatory network**

The tissue- or stage-specific expression patterns and the dynamic subcellular localizations of the miRNAs emphasize the importance of spatio-temporal co-localization of miRNA regulators and their targets for regulatory effectiveness. However, another regulatory layer, indirect targeting, should not be ignored especially when attempting to construct miRNA-mediated regulatory networks (Rubio-Somoza et al., 2009). Within the regulatory module *miR390—TAS3—ARF2/3/4, ARF2, ARF3* and *ARF4* are the indirect targets of miR390 (Marin et al., 2010). Besides, the *ARF* transcripts targeted by miR160, miR167, miR390 (Mallory et al., 2005; Wang et al., 2005; Wu et al., 2006; Yang et al., 2006a; Marin et al., 2010) encode ARF transcription factors that could interact with other ARFs and specific Aux/IAA repressors (another family of TFs) at the protein level, modulating the auxin signaling pathway in plants. Furthermore, ARFs could in turn regulate the expression of *miR160, miR167* (Gutierrez et al., 2009), or other sRNA genes transcriptionally. Thus, certain ARFs, Aux/IAAs and the sRNA genes regulated by the ARFs become the indirect targets of miR160, miR167, and miR390, contributing to the complexity of the miRNA-mediated networks. Besides, as mentioned in the above section, the
secondary siRNAs generated from the miR393-cleaved TAAR transcripts could further amplify the silencing signal involved in auxin-mediated leaf development (Si-Ammour et al., 2011).

In summary, miRNA recycling, amplification of silencing signals, dosage- and localization-dependent regulation, feedback regulation between certain miRNAs and their targets, and indirect targeting together orchestrate a fascinating, highly dynamic regulatory network with buffering system in plants (Figure 2).

THE FATE OF A MIRNA: TAILING/TRIMMING-INDUCED DECAY OR STABILIZATION

In addition to transcription, maturation, miRISC loading, and recycling, the in vivo stability greatly influences the levels of the active miRNAs. Recent evidences gained from HTS and other methods showed that a large portion of miRNAs were tailed with one to several non-templated 3’ Us or As (adenines) in both plants and animals, which served as a signal modulating the miRNA stability (Li et al., 2005; Ramachandran and Chen, 2008; Katoh et al., 2009; Lu et al., 2009; Ameres et al., 2010; Ibrahim et al., 2010; Baccarini et al., 2011). In both kingdoms, several studies reached the consensus that adenylation increased the miRNA stability whereas uridylation promoted miRNA degradation (Katoh et al., 2009; Lu et al., 2009; Ibrahim et al., 2010; Baccarini et al., 2011). However, some exceptional cases were reported at the same time. In Drosophila, highly complementary targets triggered tailing of the small silencing RNAs including the miRNA species, and both 3’ uridylation and 3’ adenylation were suggested to promote miRNA degradation, which was also conserved in human cells (Ameres et al., 2010). In Arabidopsis, in vitro analysis demonstrated that miRNAs could be uridylated at the 3’ terminals that were not methylated, and the uridylation protected those miRNAs from SDN1 (SMALL RNA DEGRADING NUCLEASE 1)-mediated degradation (Ramachandran and Chen, 2008). It seems quite complicated according to the above observations. However, the roles of terminal modifications on
miRNA stability should become more legible with the continuing research efforts on this topic. On the other hand, the 5’-to-3’ and the 3’-to-5’ trimming of miRNAs, as one means of degradation, were demonstrated to have a regulatory role in controlling the abundances of miRNAs in plants and mammalian cells (Lu et al., 2009; Ameres et al., 2010; Baccarini et al., 2011).

However, we should note that the miRNA stability can not be calculated by a simple linear equation, and is affected by numerous dynamic factors. For example, adenylation of the miRNAs in *Populus trichocarpa* showed a tissue-specific dependence (Lu et al., 2009). More interestingly, emerging evidences in animals pointed to the fact that the miRNA fate was greatly influenced by their targets. As shown in Figure 2B, the degradation rate of a miRNA was primarily affected by two factors, i.e. the complementarity and the abundance of its target. Recent study carried out by Ameres and colleagues (2010) proposed that extensive complementarity between a target transcript and a miRNA triggered tailing and 3’-to-5’ trimming of the miRNA. Considering the difference that most targets in plants are highly complementary to the miRNA regulators (Jones-Rhoades et al., 2006; Voinnet, 2009), whether the sequence complementarity has a great influence on the stability of plant miRNAs needs further investigation. One intriguing hint was obtained by Todesco et al. (2010). In that study, the authors examined the levels of targeted miRNAs in all the target mimic lines of *Arabidopsis*. The result showed that the abundances of nearly all the targeted miRNAs were significantly decreased, leading to the conclusion that interactions between the target decoys and the miRNAs could reduce the miRNA stability in plants (Todesco et al., 2010). Coincidentally, repressive regulatory role of partially complementary transcripts in controlling sRNA activities was also reported in bacteria (Figueroa-Bossi et al., 2009; Overgaard et al., 2009). Another important factor, the target abundance, was reported to possess a dilution effect on the miRNA activities after the expression-based examination in dozens of miRNA- and siRNA-transfected Hela S3 cell lines (Arvey et al., 2010). Considering the evidences above, we would like to suppose that the high abundances of the targets with high complementarity to the miRNAs in animals (maybe the bulge targets in plants) could
not only dilute the miRNA activities through sequestration, but also promote miRNA degradation more efficiently. However, even the complementarity- and abundance-dependent model of the target-induced miRNA degradation is established (Figure 2B), some exceptions can not be excluded. In *Caenorhabditis elegans*, both in *vitro* and in *vivo* analyses showed an unexpected result that miRNA degradation could be blocked by the addition of target RNAs, which was then defined as “target-mediated miRNA protection” (TMMP) (Chatterjee and Grosshans, 2009; Chatterjee et al., 2011).

In addition to the negative factors promoting miRNA decay, the miRNAs could be protected and stabilized by AGO-associated miRISCs (Vaucheret et al., 2004; Kai and Pasquinelli, 2010). As reviewed by Kai and Pasquinelli (2010), in both animals and plants, AGO proteins may function in both the biogenesis and the stabilization of the mature miRNAs (Kai and Pasquinelli, 2010). Considering the novel phenomenon TMMP discovered in *Caenorhabditis elegans* (Chatterjee and Grosshans, 2009; Chatterjee et al., 2011), we reasoned that the target-bound miRISCs could efficiently stabilize the incorporated miRNAs, and this protection may be partially dependent on the target structures (Ameres et al., 2007). As suggested by Chatterjee *et al.* (2011), TMMP adds another mutual regulatory layer between miRNAs and their targets, enabling dynamic expression and functional evolution of the miRNA genes. The early pioneer work by Vaucheret *et al.* (2004) showed that complete depletion of *AGO1* led to a drop of the abundances of some miRNAs in *Arabidopsis*, indicating the involvement of *AGO1* in miRNA biogenesis and/or stabilization (Vaucheret et al., 2004). However, things will develop in the opposite direction when they become extreme. A large excess of *AGO1* protein in transgenic plants resulted in a decrease in miRNA accumulation. The authors interpreted that excessive *AGO1* could interfere with the normal function of miRISCs and might sequester the mature miRNAs thus inhibiting their activities (Vaucheret et al., 2004). In that study, Vaucheret and colleagues also provided the first evidence for the feedback regulation between *AGO1* and miR168, and further illustrated the importance of miR168-mediated regulation of *AGO1* mRNA for proper plant development (Vaucheret et al., 2004) (Figure 2A).
follow-up experiments presented more detailed insights into this feedback regulatory module (Vaucheret et al., 2006; Mallory and Vaucheret, 2009; Vaucheret, 2009). As mentioned above, AGO proteins have great potential in participating in the biogenesis and the stabilization of miRNAs in organisms (Vaucheret et al., 2004; Vaucheret et al., 2006; Diederichs and Haber, 2007; O’Carroll et al., 2007; Cheloufi et al., 2010; Cifuentes et al., 2010; Kai and Pasquinelli, 2010; Lund et al., 2011). In plants, to prevent excessive expression of AGO1, miR168 is employed as a critical regulator controlling the abundance of AGO1 mRNAs. Interestingly, the two nodes of the feedback circuit have a common expression pattern, which was demonstrated to be coregulated transcriptionally (Vaucheret et al., 2006). Besides miR168, other regulators, both positive and negative ones were discovered to modulate the AGO1 activities in plants. Loss-of-function mutations of SQN (SQUINT), an orthologue of CyP40 (CYCLOPHILIN 40) in Arabidopsis, caused a reduction in AGO1 activity. It supports the notion that CyP40 maintains the proper function of AGO1 or the AGO1-associated silencing complexes, and it is required for the regulatory activities of plant miRNAs (Smith et al., 2009). Besides, HSP90 (HEAT SHOCK PROTEIN 90), functioning as a molecular chaperone, was demonstrated to facilitate the in vitro assembly of AGO1-associated RISCs. The ATP-dependent, HSP90-bound AGO1 complexes-mediated process could ensure correct incorporation of the functional strands of the siRNA duplexes into the designated RISCs (Iki et al., 2010). There are also several negative regulators modulating the activities of AGO1. During a screening for the mutations suppressing the sqn phenotype, Earley et al. (2010) identified the F-box gene FBW2 (F-BOX WITH WD-40 2), which was further shown to negatively regulate the abundance of AGO1 at the protein level in Arabidopsis (Earley et al., 2010). In aged fly brain, the Drosophila AGO1 protein level is negatively regulated by LRRK2 (LEUCINE-RICH REPEAT KINASE 2) (Gehrke et al., 2010). More interestingly, the siRNAs derived from the transcripts of AGO1 itself could trigger AGO1 cosuppression through RDR6-, SGS3 (SUPPRESSOR OF GENE SILENCING 3)-, SDE5 (SILENCING DEFECTIVE 5)-, and DCL2/4-dependent silencing pathway in Arabidopsis (Mallory and Vaucheret, 2009) (Figure 2A). Further,
the authors showed that the siRNA-mediated AGO1 silencing depended on the correct cleavages of AGO1 transcripts by miR168, pointing to the coordinated regulatory actions of the miRNA and the siRNA pathways for maintaining the AGO1 homeostasis.

Taken together, non-templated 3’ tailing has a significant impact on the stabilization of the miRNAs. The miRNA degradation rate is highly dependent on the abundances and the complementarity of its targets. The AGO-associated miRISCs have a protective role for the mature miRNAs. More complicatedly, the activities of AGO1 and its associated silencing complex are also under strict surveillance. All the factors make the in vivo activities of the plant miRNAs more variable and more tolerant to the external fluctuations.

MIRNA DYNAMICS, IN AN EVOLUTIONARY PERSPECTIVE

As introduced in the above sections, the spatio-temporal transcription and processing, the loading competition, the feedback regulation, the miRNA recycling, the buffering system, and the target-dependent decay all together contribute to the dynamic activities of plant miRNAs. Apart from these aspects, the evolution of miRNA processing and functional diversification also underscores the dynamic nature of miRNA-based regulation in the complex regulatory networks (Allen et al., 2004; Cuperus et al., 2011). The miRNA genes were suggested to originate from the inverted repeats (IRs) that could form self-complementary regions, such as the non-autonomous transposons containing flanking terminal IRs (Allen et al., 2004; Vazquez et al., 2010; Cuperus et al., 2011). During the evolutionary history, new miRNA families were spawned, and some might be lost at a high frequency. The transitionary loci of the newly born miRNA genes may be difficult to identify since some indivisible intersections exist between the miRNA and the siRNA pathways (Cuperus et al., 2011). From the proto-miRNAs, to the IR-miRNAs, then to the young miRNAs, and finally to the highly conserved miRNA genes (Vazquez et al., 2010), the evolution of the miRNA genes were indicated to be a neutral process (Cuperus et al.,
However, we could not completely exclude the selective evolutionary process that the miRNAs with essential biological roles might be preferentially retained and functionally diversified in different plant species, while the functionally inert ones tend to be deserted more frequently.

The dynamic evolution may also lead to the discrepancy of miRNA processing and action between the plant and the animal systems. The established miRNA-mediated regulatory modes tell us that the plant miRNAs recognize and cleave the target transcripts with high complementarity whereas in animals, the imperfect interactions between specific miRNAs and their targets lead to translational repression in most cases (Carthew and Sontheimer, 2009; Voinnet, 2009). Considering the notion mentioned above that high target complementarity might result in elevated degradation rate of mature miRNAs (Figure 2B), we suspect that the evolved HEN1-mediated 3’ methylation of miRNA/miRNA* duplexes in plants could protect the miRNAs from tailing and trimming when interact with the highly complementary targets (Li et al., 2005; Yu et al., 2005). On the other hand, the relatively low complementarity between the targets and the animal miRNAs might be able to compensate for the lack of the methylation machinery for miRNA maturation. Supportively, the maturation of piRNAs [Piwi (P-element induced wimpy testis)-interacting RNAs] in animals, which function in transposon silencing in germline cells, requires 3’ trimming and methylation. Similar to the most miRNA—target interactions in plants, the targets are highly complementary to the piRNAs (Vagin et al., 2006; Horwich et al., 2007; Saito et al., 2007; Kurth and Mochizuki, 2009; Senti and Brennecke, 2010). Another evidence provided by Ameres et al.’s study (2010) showed that the Drosophila AGO2-bound siRNAs targeting viral and transposon RNAs with high complementarity possessed a 2’-O-methyl group at their 3’ ends, while the AGO1-associated miRNAs did not. More interestingly, increasing the complementarity between a target transcript and the regulatory miRNA could significantly reduce its stability by triggering tailing and 3’-to-5’ trimming of this unmethylated miRNA (Ameres et al., 2010). Whether these observations indicate the nexus of the coevolved miRNA-mediated regulatory systems between the plants
and the animals needs clarification.

**TOWARD THE GENUINE ACTIVITIES OF MIRNAS**

In this review, we summarized all the major processes, i.e. transcriptional control, processing and maturation, miRISC loading, and miRNA action and fate, influencing the *in vivo* levels of plant miRNAs. Based on the current reports in both plants and animals, numerous important factors embedded within each process were presented, which made great contributions to the dynamic nature of the regulatory activities of miRNAs. In addition to the spatio-temporal expression of the miRNA—target pairs and the machineries responsible for miRNA processing and action, and miRNA-involved loading competition, several novel actions, such as recycling, buffering, feedback regulation, secondary amplification, and target-dependent stabilization, converge to a quite complex equation for miRNA activity calculation. Furthermore, both the birth and the death, and the functional diversification of miRNA genes represent another dynamic aspect of the plant miRNA genes. All these dynamic features of miRNAs infuse more energy to the buffering systems of the gene regulatory networks in plants.

Finally, we would like to emphasize the importance of taking all the variable elements into account when assessing the real activities of miRNAs *in planta*. At the same time, more and more such factors are being uncovered. It is foreseeable that once the comprehensive equation is reached, the miRNA activities could be precisely quantified by drawing an elaborate curve showing its dynamic variation in a specific cellular context.

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FIGURE LEGENDS

Figure 1. Schematic presentation showing the dynamic nature of microRNA (miRNA) biogenesis in plants. A, RNA polymerase II (Pol II)-dependent transcription of the miRNA genes. Chromatin marks including DNA methylation and histone modifications, and the combinatorial regulation of many transcription factors (TFs) together contribute the spatio-temporal expression patterns of the miRNA genes in plants. B, Processing of miRNA precursors and miRNA maturation. RNA editing on the miRNA precursors plays a role in changing the original sequence information encoded by the miRNA gene loci. The exosome was suggested to be implicated in digesting the processing intermediates from the miRNA precursors, ensuring
relatively high processing efficiency. The processing efficiency also shows a high precursor sequence-specific dependence. Methylation at the 3’ ends of the miRNA/miRNA* duplex (“Me” in this figure panel represents the methyl group) is crucial for the stabilization of the miRNA and the miRNA*. A feedback circuit between DCL1 (Dicer-like 1) and miR162 exists within the processing procedure. Moreover, the siRNAs (small interfering RNAs) complementary to the specific pri-miRNAs (primary microRNAs) and the pre-miRNAs (precursor microRNAs) exhibit a potential repressive role in miRNA processing. More interestingly, the pri-miRNAs and the pre-miRNAs may possess their own targets. C, Sorting into the AGO (Argonaute)-associated miRISCs (microRNA-induced silencing complexes). A drastic loading competition may exist among miRNAs, miRNA*s, and other small RNA (sRNA) species. Not all the miRNAs are incorporated into the AGO1 complex. The 5’ terminal composition and the sequence length of the miRNAs, the structure of the miRNA/miRNA* duplex, and other undetermined factors have a significant influence on the loading patterns of the mature miRNAs.

**Figure 2.** Schematic summarization of the factors influencing microRNA (miRNA) action and the *in vivo* levels. A, Based on the recent reports in animals, the turnover use of the mature miRNAs is proposed in plants, which needs further validation (denoted by a question mark). The 3’ tailing and the 3’-to-5’ trimming greatly affect the stability of the mature miRNAs. Certain miRNA targets, such as transcription factor genes, could in turn regulate the miRNAs, thus forming feedback regulatory circuits. The secondary siRNAs (small interfering RNAs) amplified from the cleaved target transcripts of a specific miRNA could reinforce the miRNA-mediated gene silencing post-transcriptionally. One example is provided by the feedback circuit between AGO1 (Argonaute 1) and miR168 in Arabidopsis. The secondary siRNAs derived from miR168-cleaved AGO1 transcripts could further regulate the expression of AGO1 post-transcriptionally. On the other hand, the abundance of the AGO1 protein significantly affects the activities and the stability of numerous miRNAs. B, The adjustable turnover rate of certain miRNAs may form an elaborate buffering system.
within the miRNA-mediated regulatory networks, which needs further investigation (denoted by a question mark in the left panel). Based on the current hints in plants and animals, a target abundance- and complementarity-dependent model was proposed to be implicated in modulating the miRNA degradation rate (the right panel). C, Based on the phenomenon “target mimicry” observed by Franco-Zorrilla et al. (2007), the miRNA could be sequestered by a target decoy with a central bulge within the target recognition sites. Thus, the miRNA turnover will be inhibited in that case. Although it is still not clear, the 3’ tailing and the 3’-to-5’ trimming may also occur on the miRNAs sequestered by the bulged targets (also denoted by question marks).
A. Secondary siRNA production leads to reinforced repression and homologous targets.

B. Changes in turnover rates and miRNA abundance over time scale and degradation rate.

C. Trimming and tailing processes affect miRNA stability and RISC complex interaction with AGO1.