

1 Identification of genes preferentially expressed in wheat egg cells and zygotes

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4 Mónika Domoki^{1,#}, Attila Szűcs^{1,#}, Katalin Jäger², Sándor Bottka¹, Beáta Barnabás², Attila

5 Fehér^{1*}

6 ¹ Institute of Plant Biology, Biological Research Centre, Hungarian Academy of Sciences,

7 Temesvári krt. 62, H-6726, Szeged, Hungary

8 ² Agricultural Institute, Centre for Agricultural Research, Hungarian Academy of Sciences,

9 Brunszvik u. 2, H-2462, Martonvásár, Hungary

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22 [#] These authors contributed equally to the research.

23 ^{*} Author for correspondence: Attila Fehér, Institute of Plant Biology, BRC, HAS, 6701

24 Szeged, P.O.Box 521., Hungary. E-mail: feher.attila@brc.mta.hu

1 **Abstract**

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3 In order to have an insight into fertilization-induced gene expression, cDNA libraries have
4 been prepared from isolated wheat egg cells and one-celled zygotes. Two-hundred and
5 twenty-six egg cell and 253 zygote expressed EST sequences were determined. Most of the
6 represented transcripts were detected in the wheat egg cell or zygote transcriptome at the first
7 time. Expression analysis of fourteen of the identified genes and three controls was carried
8 out by real-time quantitative PCR. The preferential expression of all investigated genes in the
9 female gametophyte-derived samples (egg cells, zygotes, two-celled proembryos, and basal
10 ovule parts with synergids) in comparison to the anthers, and the leaves were verified. Three
11 genes with putative signaling/regulatory functions were expressed at a low level in the egg
12 cell but exhibited increased (2-to-33-fold) relative expression in the zygote and the
13 proembryo. Genes with high EST abundance in cDNA libraries exhibited strong expression in
14 the egg-cell and the zygote, while the ones coding for unknown or hypothetical proteins
15 exhibited differential expression patterns with preferential transcript accumulation in egg cells
16 and/or zygotes. The obtained data support the activation of the zygotic genome before the first
17 cell division in wheat.

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20 Key words: EST sequencing, expressed sequence tag, female gametophyte, fertilization, gene
21 expression, plant, proembryo, real-time quantitative PCR, *Triticum aestivum* L.

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- 1 Key message: Wheat genes differentially expressed in the egg cell before and after
- 2 fertilization were identified. The data support zygotic gene activation before the first cell
- 3 division in wheat.
- 4

1 **Introduction**

2

3 The life cycle of plants can be divided into a diploid sporophytic and a haploid gametophytic
4 phase. Most of our knowledge on plants comes from dominant sporophytes, because the
5 gametophytes, which consist of only a few cells, are encapsulated in the tissues of the
6 sporophytic generation. Recent advances in plant molecular biology allowed us to have deeper
7 insights into the plant gametophyte development (for reviews; Yang et al. 2010; Sundaresan
8 and Alandete-Saez 2010; Borg and Twell 2010 ; Borg et al. 2009).

9 The female gametophyte of angiosperms typically consists of one egg cell, one central cell,
10 two synergid and three antipodal cells. These cell types all have unique structural features and
11 functions to ensure the success of the reproductive process. Modern, high-throughput
12 techniques allowed studying of the transcriptome of these specialized cells in model species
13 (for review; Schmidt et al. 2012b). Functional characterization of the transcripts revealed
14 differences highlighting specific posttranscriptional regulatory modules and metabolic
15 pathways characteristic for each female gametophytic cell type (Wuest et al. 2010). However,
16 comparison of transcripts enriched in the egg and synergid cells, respectively, of *Arabidopsis*
17 and rice also revealed considerable species-specific differences in the molecular networks
18 underlying gametophyte development and function (Ohnishi et al. 2011).

19 The egg cell has a distinct role in the female gametophyte because it acts as a signaling center
20 for the development of all female gametophytic cells (Volz et al. 2012) and develops to the
21 new sporophytic generation after fertilization. Wuest and coworkers (Wuest et al. 2010) could
22 identify 431 genes which are likely to be specifically expressed in the mature female
23 gametophyte of *Arabidopsis thaliana* of which 163 was specifically expressed in the egg. In
24 animals, maternally deposited mRNAs in the egg cell control early embryonic development

1 before the activation of the zygotic genome (Minami et al. 2007). Although, based on various
2 experimental data, a similar period of maternal control on early embryogenesis was
3 hypothesized for plants as well (Baroux et al. 2008), a recent comprehensive study revealed
4 that the zygotic genome is activated right before the first cell division and the earliest phases
5 of embryogenesis are mostly under zygotic control in Arabidopsis (Nodine and Bartel 2012).
6 Comparative gene expression profiling of tobacco egg cells, one- and two-celled zygotes
7 resulted in a similar conclusion (Zhao et al. 2011).

8 Wheat (*Triticum aestivum* L.) is one of the most important crops worldwide. Identification of
9 wheat genes and proteins, determining egg cell development and identity, fertilization
10 success, and early embryogenesis, is of great significance for future practical applications in
11 addition to their scientific value. However, wheat has a huge and complex genome that could
12 not have been fully revealed and therefore, the adaptation of high throughput genomic
13 methods for this species are still limited (Gupta et al. 2008). In contrast, there are routine
14 methodologies for the isolation and culture of the cell types of the wheat female gametophyte
15 (Kovács et al. 1994; Kumlehn et al. 1999; 2001). Therefore the analysis of gene expression
16 profiles of wheat egg cells and zygotes via EST sequencing is feasible.

17 It was well demonstrated by Sprunck and her coworkers, who prepared cDNA libraries from
18 isolated wheat egg cells and two-celled proembryos (Sprunck et al. 2005). They determined
19 404 and 789 EST sequences, respectively, and based on the data, compared the expression
20 profiles of the egg cell and the two-celled proembryo. They concluded that the unfertilized
21 wheat egg cell has a higher metabolic activity and protein turnover than previously thought.
22 Moreover, they found that the transcript composition of the proembryos is significantly
23 distinct from that of the egg cells. Transcripts, associated with DNA replication as well as

1 with high transcriptional and translational activity, characterize the transcriptome of the
2 dividing zygote.

3 More recently, Kőszegi and colleagues (Kőszegi et al. 2011) coupled EST sequencing with a
4 cDNA subtraction approach and identified the egg cell-specific RKD transcription factors
5 regulating several egg cell-specific genes.

6 Here an EST sequencing approach is reported using unfertilized wheat egg cells and single-
7 celled zygotes (seven hours after fertilization) for cDNA library production and EST
8 sequencing. The obtained data complement of those reported by Sprunck and her co-workers
9 (Sprunck et al. 2005) providing information on single-celled zygote- and further egg cell-
10 expressed genes of wheat. Furthermore, the reported gene expression analysis of selected
11 genes supports the activation of zygotic genes before the first cell division in wheat as well.

12

13 **Materials and methods**

14

15 *Plant material, cultivation and sample collection*

16 Plants of a spring wheat (*Triticum aestivum* L.) genotype Siete Cerros were used in the
17 experiment. After germination, plants were vernalized for five weeks at 2 °C and transplanted
18 into a sand-soil-peat (1:3:1) mixture (2 kg/pot). Plants were grown in controlled conditions
19 until flowering in a PGR-15 phytotron chamber using the climatic program T2 (Tischner et al.
20 1997) at a light intensity of 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 8 weeks. During this period, the initial
21 max/min day/night temperature was increased from 12.5/5.5 °C to 23/14 °C. Vernalization
22 was applied to spring wheat, because the initial max/min day/night temperature of the T2
23 climatic program was not sufficient to induce the vegetative/generative transition. The relative

1 day/night humidity of the air circulating in the chamber was 65/75%. The photosynthetic
2 photon flux density during cultivation was $500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.
3 Plants were emasculated, and the spikes were protected with cellophane bags to avoid self-
4 and cross-pollination four days before anthesis. Reference spikes were also used in order to
5 check the efficiency of emasculation and hand pollination, which was above 95 %. Prior to
6 egg cell, zygote, proembryo and ovule isolation, the spikes were surface sterilized with 2%
7 (v/v) sodium hypochlorite for 20 minutes and washed four times with sterile distilled water.
8 Egg cells (Fig. 1A,B; n=50), were isolated from non-pollinated pistils, single-celled zygotes
9 (fertilized egg cells at around the time of karyogamy) (Fig. 1C,D; n=50), and two-celled
10 proembryos (Fig. 1E,F; n=50), from hand-pollinated pistils 7 and 24 hours after pollination
11 (HAP), respectively, according to the method described earlier by Kovács et al. (Kovács et al.
12 1994).
13 Basal ovule parts (n=50), containing the synergids, isolated from non-pollinated, 7 HAP and
14 24 HAP pistils were collected after egg cell, zygote and proembryo isolation, respectively.
15 Anthers (n=12) were collected in tricellular stage of pollen development, one day before
16 anthesis. All the samples above were collected in 10-10 μl -s of the Lysis/Binding buffer of the
17 „Dynabeads mRNA Direct” RNA isolation kit (Invitrogen, USA) in three repetitions. Leaf
18 samples (3 mg each) were excised from 5-day-old seedlings and placed into RNAlater
19 solution (Invitrogen) in three repetitions. The RNAlater solution was changed for 100 μl
20 Lysis/Binding buffer before RNA isolation.

21

22 *mRNA isolation and cDNA library preparation*

23 mRNA isolation was carried out according to the protocol provided by the manufacturer
24 („Dynabeads mRNA Direct” RNA isolation kit; Invitrogen) after adding 90 μl -s of

1 Lysis/Binding buffer and 10 μ l oligo-dT-coated Dynabeads to the samples. The mRNA
2 samples have been eluted into 5 μ l sterile water and were immediately used in total for cDNA
3 library preparation using the „SMART cDNA Library Construction Kit” (Clontech
4 Laboratories, USA). First strand cDNAs have been synthesized by Superscript II reverse-
5 transcriptase (Invitrogen) using the adaptors provided in the kit. Two-stranded cDNA was
6 produced by PCR amplification for 30 cycles due to the limited starting material. This number
7 of cycles still resulted in exponential target amplification as determined experimentally (data
8 not shown). The adaptor-containing cDNAs were digested by Sfi I and ligated to Δ TriplEx2
9 phagemid arms. Recombinant phages were produced using the Gigapack III Gold Packaging
10 Extract (Stratagen, USA).

11

12 *EST sequencing*

13 Individual phage plaques were converted to pTriplEx2 plasmids using *Escherichia coli*
14 BM25.8 as a host as described in the manual of the cDNA library construction kit. Plasmid
15 DNAs were purified using a modified alkali lysis protocol (Feliciello and Chinali 1993).
16 Colony PCR has been carried out using pTriplEx2 5' sequencing (5'
17 TCCGAGATCTGGACGAGC 3') and the T7 promoter (5'
18 TAATACGACTCACTATAGGGC 3') primers at 94°C 5' 1x, 94°C 15'' 52°C 30'' 72°C 1'
19 30'' 28x, 72°C 5' 1x PCR cycle parameters using Fermentas (Lithuania) Taq DNA
20 polymerase. Plasmids with inserts >100 bp have been selected for sequencing by Macrogene
21 Inc. (Korea) using the pTriplEx2 5' sequencing primer. The EST sequences derived from the
22 egg cell were designated as EPS# and those from the zygote as ZIG#. The sequences have
23 been deposited in the EMBL Nucleotide Sequence Database with the accession numbers
24 HE862417-HE862958 (<http://www.ebi.ac.uk/embl/>).

1

2 *Sequence analysis and annotation*

3 The homology of vector sequence-free ESTs to database sequences was investigated using the
4 NCBI BLAST server (<http://blast.ncbi.nlm.nih.gov/Blast.cgi>). Sequence annotation and
5 annotation analysis were carried out by the BLAST2GO analysis tool (Götz et al. 2008) using
6 default settings.

7

8 *Real-time quantitative PCR*

9 mRNA isolation and cDNA synthesis were made as described above for cDNA library
10 preparation. For real time quantitative PCR (RT-QPCR) assays and evaluations, an ABI
11 7900HT equipment and its software (SDS version 2.3; Applied Biosystems, USA) were used
12 based on SYBR-green detection and $\Delta\Delta CT$ analysis as described elsewhere in more details
13 (Szűcs et al. 2006). Three assays were carried out on independent samples with at least two
14 parallel measurements each. The RT-QPCR master mix was purchased from Applied
15 Biosystems. The primers used are listed in Supplementary material 1.

16

1 **Results**

2

3 **The cDNA libraries**

4 The cDNA libraries contain approximately $2,4 \times 10^6$ and $0,45 \times 10^6$ individual recombinant
5 phages in the cases of un-fertilized egg cells and one-celled zygotes, respectively, based on
6 the phage titer and the ratio of insert containing/empty phagemids. The average insert size
7 was determined as 490 bp for egg cell ESTs (EPS) and 416 bp for zygote ESTs (ZIG). The
8 redundancy of the clones was low as the randomly selected 246 egg cell EST sequences
9 represented 226, while the 297 zygote ones 253, different genes (singletons).

10

11 **Characterization of EST sequences of wheat genes expressed before and/or after**
12 **fertilization**

13 Randomly selected recombinant phagemids (300-300 from both libraries) have been
14 converted into pTripleEx2 plasmid clones. Plasmids carrying inserts larger than 100 bp have
15 been purified and subjected to sequencing using a 5' pTriplEx2 vector primer. As a result,
16 246 EPS and 297 ZIG high quality sequences could be obtained. The ESTs have been
17 subjected to BLAST analysis and annotation following the *in silico* removal of vector
18 sequences. Detailed results of these analyses are summarized as Supplementary material 2
19 (egg cell) and 3 (zygote).

20 Some of the genes were represented by several ESTs (Table 1) that may indicate abundant
21 expression in the given cell type. However, it has to be taken into account that the cDNA
22 library has been made by SMART PCR. The advantage of using the SMART PCR method is
23 that it preferentially enriches for full-length transcripts. However, in doing so, it may
24 introduce compositional biases and alter the relative abundance of transcripts. In the EPS

1 library, sequences representing TA64547_4565 coding for a putative dihydrolipoamide
2 dehydrogenase were found to be the most redundant (7 occurrences) while in the ZIG library
3 CD889724 coding for a hypothetical protein (12 occurrences).

4 From the 246 EPS sequences, 208 showed similarity to database sequences based on the
5 BLASTX algorithm (among which 76 was similar to hypothetical or expressed proteins with
6 no known function), and a further 19 using only the BLASTN homology search. The
7 remaining 19 sequences had no homology to known ESTs/genes/proteins. Considering the
8 ZIG ESTs, these numbers were: 297 total; 258 BLASTX (113 hypothetical or expressed
9 proteins); 21 only BLASTN; 18 no homology.

10 It was also tested how many of the ESTs correspond to transcripts that have already been
11 found to occur in egg cell or zygote cDNA libraries based on the sequences stored in the
12 "Wheat Transcript assembly 2" dataset from TIGR (The Institute for Genomic Research;
13 updated July 2007). The overlap was minimal (<1%) indicating that most of the identified
14 EST sequences carry novel information on the expression of genes in wheat egg cells and
15 zygotes.

16

17 **Selection of genes for expression analysis**

18 Fourteen sequences have been selected for further gene expression analysis based on the
19 annotation of the represented genes.

20 Three of the ZIG ESTs were selected because they represent genes with putative roles in
21 signal transduction (ZIG75 was annotated as putative mitogen-activated protein kinase kinase,
22 TaMAPKK) and transcriptional regulation (ZIG43 was annotated as E2F transcription factor-
23 like, TaE2F; ZIG45 was annotated as transcription factor B3-like, TaTFB3). Due to their
24 potential regulatory functions, it was to be investigated whether their transcription is induced

1 by fertilization. The relative expression of the TaSERK3 gene coding for a putative somatic
2 embryogenesis receptor kinase was also determined to serve as a kind of control as the protein
3 was hypothesized to have a role in zygotic embryogenesis (Singla et al. 2008).
4 Further four zygote-expressed sequences (ZIG 47,253, 298 303,) were selected based on their
5 unique sequences. As they have no sequence homologues in the available databases, we
6 supposed that at least some of them may have fertilization/zygote specific expression pattern.
7 A similar approach was followed by Kőszegi et al. (2011) who identified in this way the egg-
8 cell-specific members of the wheat RKD transcription factor family.
9 From the egg cell library, five ESTs (EPS 47, 49, 104, 124, and 282) were randomly selected
10 from those that represented genes that code for hypothetical proteins or had no homologous
11 sequences in the protein databases as determined by the BLASTX algorithm.
12 EPS76 and EPS87 sequences were chosen as positive controls as they have several ESTs but
13 only from wheat egg cell-derived cDNA libraries, therefore, they may code for egg cell-
14 specific transcripts. The EPS76 represented gene (TaECA1) is homologous to a barley
15 (*Hordeum vulgare* L.) gene the product of which is annotated as “Early Culture Abundant
16 Protein 1” (HvECA1, gene bank accession: AAF23356.1) as it is expressed in embryogenic
17 microspore cultures during the early culture phase (Vrinten et al. 1999). The gene represented
18 by the EST sequence EPS87 (TaDSUL) codes for a protein with small ubiquitin-like modifier
19 (SUMO) and ubiquitin-like domains (di-SUMO-like or DSUL, gene bank accession:
20 ACL50300.1). Recently, the maize homologue of this protein has been characterized in detail
21 by Srilunchang et al. (Srilunchang et al. 2010) who specified that it is required for nuclei
22 positioning, cell specification and viability during female gametophyte maturation.
23 In order to have appropriate reference genes expressed ubiquitously in the wheat plant,
24 including the egg cell and zygote, the “Wheat Transcript assembly 2” dataset from TIGR has

1 been analyzed for genes equally represented by EST sequences in various wheat cDNA
2 libraries (including those made from egg cells or zygotes). Two of the genes, coding for a
3 putative NADPH oxidase (TA61480_4565) and for a hypothetical ubiquitin conjugase
4 (TaUBC; TA64564_4565), respectively, identified by this *in silico* gene expression approach
5 (for details see Szűcs et al. 2010) were used as reference genes in the RT-QPCR experiments.

6

7 **Gene expression analysis**

8 Samples were collected from mature egg cells (at anthesis), one-celled zygotes (7 HAP),
9 proembryos (24 HAP) (see Fig.1.), and from the lower ovule parts, they were removed off (at
10 anthesis, 7 and 24 HAP), as well as from anthers and young leaves.

11 As it is shown on Fig. 2, the relative expression of the four investigated genes annotated as
12 having potential functions in signaling/transcription (TaMAPKK, TaE2F, TaTFB3,
13 TaSERK3) was lower in leaves or anthers in comparison to the ovule-derived samples. Three
14 of them exhibited an increase in their relative mRNA level in response to the fertilization (in
15 the zygote/proembryo versus the egg cell). This increase was strong (more than 20-fold and 5-
16 fold, respectively) in the case of the two transcription factors TaTFB3 and TaE2F. The
17 relative expression of the TaSERK3 gene was the highest in the ovules. Its expression was
18 increased by more than 2-fold in the fertilized egg cell and the one-day-old zygote as
19 compared to the unfertilized egg cell. The TaMAPKK gene showed a rather constitutive
20 expression in these samples. As far as the relative expression of these genes in the egg cell is
21 considered, the TaMAPKK gene exhibited a high relative expression (similar to the
22 expression level of the reference gene coding for an ubiquitin conjugase) while the transcripts
23 of the three other genes were much less abundant (app. two orders of magnitude lower
24 abundance).

1 The nine genes represented by ESTs with no homology to known sequences and the two
2 control ones (TaECA1; TaDSUL) all exhibited strong egg cell/zygote/proembryo-specific
3 relative expression as compared to ovule-parts, anthers and leaves. These genes were
4 classified into four categories based on their expression pattern. TaDSUL, TaECA1, EPS49,
5 EPS104, and ZIG298 exhibited decreased expression in the proembryo in comparison to the
6 egg cell and zygote where they were expressed at more or less the same level (Fig. 3A).
7 EPS124 and ZIG47 genes exhibited a rather constitutive expression in these cell types (Fig.
8 3B). EPS47, and ZIG253 showed a moderately (2-to-3-fold) increased zygotic expression
9 (Fig. 3C), while EPS282, and ZIG303, showed a high increase in their relative mRNA levels
10 in the zygote and proembryo as compared to the egg cell (Fig. 3D).

11 The normalized mRNA levels of the selected genes were compared in the egg cell in order to
12 have a view on their relative expression strength in this cell type (Fig. 3E). Based on this
13 parameter, the genes could be classified into three categories. The EPS47 gene exhibited a
14 rather low expression level in the egg cell. In contrast, the two genes with egg cell-specific *in*
15 *silico* expression pattern (TaECA1 and TaDSUL) as well as another gene represented by
16 EPS104 exhibited a strong relative expression in this cell type. The further seven investigated
17 genes showed an “intermediate” expression level as compared to the two above groups.

18

19 **Discussion**

20

21 Egg cells of Angiosperms develop from a single megaspore mother cell through a series of
22 meiotic and mitotic divisions together with the three other cell-types of the female
23 gametophyte, the synergids, the antipodal cells and the central cell. Unfolding of
24 developmental pathways leading towards the formation of the female gametophyte, including

1 pattern formation and cell specification, recently achieved considerable progress due to
2 studies of *Arabidopsis* mutants (for reviews; Sundaresan and Alandete-Saez 2010; Yang et
3 al. 2010). However, the unique features of the egg cell underlying its biochemical identity,
4 metabolic activity, and developmental potential are still poorly understood (Russell 1993).
5 Recent genomic approaches allowed a deep insight into the egg cell transcriptome of the
6 model species *Arabidopsis* and rice (Wuest et al. 2010; Ohnishi et al. 2011) and these data
7 indicate considerable species-specific differences.

8 Here, the production of a representative phagemid cDNA library prepared from isolated wheat
9 egg cells (and from one-celled zygotes; see further) is reported. The low redundancy of the
10 library allowed the identification of more than two-hundred new wheat egg-cell transcribed
11 genes via EST sequencing (see Supplementary material 2 for the detailed gene list).

12 The EST sequence population generated in this study hardly have any overlap with those that
13 have been previously deposited in public databases by others using similar approaches. A
14 possible explanation is the use of different methods for cDNA library preparation and
15 sequencing. The SMART cDNA Library technology applied in the present study resulted in
16 the enrichment of full-length cDNA sequences, which are cloned directionally into the
17 pTriplEx2 phagemid vector. As we used the 5' pTriplEx2 sequencing primer for EST
18 generation, our data represent 5' non-coding and coding sequences underrepresented in other
19 EST populations generated from unidirectionally cloned cDNA fragments (e.g. by Sprunck et
20 al. 2005). In the absence of the wheat genome sequence, it cannot be excluded, however, that
21 the same transcripts are represented by different non-overlapping ESTs in the various studies.

22 The EST sequencing approach was also suitable for the identification of transcripts with
23 preferential accumulation in the egg cell. As the result of a similar study, Sprunck and co-
24 workers (Sprunck et al. 2005) have reported several genes to be expressed specifically in the

1 wheat egg cell and two-celled zygote (proembryo) in comparison to vegetative cells. More
2 recently, Kőszegi et al. (2011) reported on the identification of wheat egg cell-expressed
3 transcription factors belonging to the plant-specific RKD family. The ectopic expression of
4 the Arabidopsis homologues of these transcription factors induced proliferation and the
5 expression of egg cell-specific genes in vegetative tissues (Kőszegi et al. 2011). These
6 previous studies clearly indicated the potentials of the EST sequencing approach in cell-
7 specific transcript identification. We could extend the wheat female gametophyte-specific
8 gene set via analyzing the expression of nine egg cell and zygote ESTs that code for unknown
9 or hypothetical proteins. The assumption that the under-representation of these sequences in
10 the databases is due to their cell/development specific expression pattern was validated by
11 RT-QPCR analysis.

12 Fertilization, the fusion of female and male gametes of sexually reproducing multicellular
13 organisms initiates a series of events (maternal-to-zygotic transition, MZT) that finally leads
14 to the development of a new organism through embryogenesis. The timing of zygotic gene
15 activation (ZGA) in plants is somewhat controversial (Baroux et al. 2008; Zhao et al. 2011;
16 Nodine and Bartel 2012). Recent data, however, indicate that it follows fertilization very early
17 and the first steps of embryogenesis are mostly under zygotic control in Arabidopsis and
18 tobacco (Nodine and Bartel 2012; Zhao et al. 2011). In animals, the extent of maternal
19 control and the timing of MZT vary greatly among species, and the MZT not always
20 coincides with the gradual process of ZGA (for review; Shen-Orr et al. 2010). The variability
21 in the timing and the molecular background of ZGA and MZT among plant species is
22 currently unknown.

23 Sprunck et al. (Sprunck et al. 2005) compared a set of ESTs from one day-old two-celled
24 wheat zygotes to that of mature egg cells. Their EST sequencing data, complemented by the

1 expression analysis of selected genes, indicated that the zygotic genome is already activated
2 in the proembryos. In the present work, we complemented these data selecting an earlier time
3 point (7HAP) for the isolation of zygotes. It was supposed that at this rather early time point
4 the direct effect of the fertilization event on the zygotic transcriptome can be investigated
5 including the activation of genes associated with the cell cycle entry. Moreover, in this way,
6 we could also define whether ZGA precedes the first zygotic cell division in wheat. The
7 increased relative expression of several genes in the single-celled wheat zygote in comparison
8 to the egg cell indeed indicated a very early ZGA in wheat. Similar assumption was obtained
9 by the comparison of gene expression in tobacco egg cells and one-celled zygotes using
10 cDNA subtraction (Ning et al. 2006) and EST sequencing (Zhao et al. 2011) approaches.
11 Therefore, Arabidopsis, tobacco and wheat data support that ZGA starts in plants before the
12 first cell division of the zygote.

13 The EST sequences generated for this study hardly have any overlap with those that have
14 been previously deposited in public databases by others using similar approaches. A possible
15 explanation is the use of different methods for cDNA library preparation and sequencing. The
16 SMART cDNA Library technology applied in the present study resulted in the enrichment of
17 full-length cDNA sequences, which are cloned directionally into the pTriplEx2 phagemid
18 vector. As we used the 5' pTriplEx2 sequencing primer for EST generation, our data represent
19 5' non-coding and coding sequences underrepresented in other EST populations generated
20 from unidirectionally cloned cDNA fragments (e.g. by Sprunck et al. 2005). In the absence of
21 the wheat genome sequence, it cannot be excluded, however, that the same transcripts are
22 represented by different non-overlapping ESTs in the various studies.

23 Although in the present study only a relatively low number of egg cell and zygotic ESTs were
24 sequenced (less than 300 each), the transcripts related to signaling (e.g. MAPKK), cell cycle

1 progression (E2F transcription factor, Cullin, Skp1, etc.) or transcription (A2 and B3 domain
2 transcription factors, etc.) were enriched among the zygotic ones (see the whole gene lists as
3 Supplementary materials 2 and 3). The expression of three of these genes (MAPKK, E2F,
4 and TFB3) was analyzed in more detail. MAP-kinase cascades are central to mitogen
5 signaling in eukaryotes, including plants (Mishra et al. 2006), and the role of specific
6 MAPKKs (upstream regulators of MAPKKs) in the post-fertilization signaling events of
7 *Solanum chacoense* ovules has already been demonstrated (Gray-Mitsumune et al. 2006).
8 Although we could not see a strong induction in the expression of TaMAPKK, one can
9 suppose that the activity of this kinase is regulated post-translationally in response to
10 fertilization.

11 The low relative expression level of the transcription factors E2F and TFB3 in the egg cell
12 was found to be considerably augmented in response to fertilization. It has to be emphasized
13 that E2F transcription factors are important regulators of the cell cycle (especially at the
14 G0/G1-S cell cycle phase transition; Berckmans and De Veylder 2009); several B3-domain
15 transcription factors have been associated with the initiation and progression of
16 embryogenesis (Suzuki and McCarty 2008). Therefore, a similar role for TaE2F in the first
17 zygotic cell division, and TaTFB3 in embryogenesis, may also be hypothesized based on their
18 sequence homology and expression pattern. In contrast, the relative expression of the
19 TaSERK3 gene previously hypothesized to be associated with embryogenesis (Singla et
20 (Singlaal. 2008) was lower in the egg cell, zygote and proembryo as compared to the ovule
21 from where these cells have been removed. This indicates a more general role for this kinase
22 in the gametophyte development.

23 The preferentially egg cell-specific expression of TaECA1 and TaDSUL the transcripts of
24 which were abundantly represented among wheat egg cell ESTs (Sprunck et al. 2005 and the

1 present study) was confirmed by RT-QPCR analysis. The maize homologue of TaDSUL, a
2 protein may be involved in the post-translational regulation of other proteins by sumoylation
3 during female gametophyte maturation (Srilunchang et al. 2010). This gene was reported to
4 be exclusively expressed in the micropylar region of the immature female gametophyte, while
5 after cellularization its expression was restricted to the egg cell and the zygote (Srilunchang et
6 al. 2010). The transcripts coding for HvECA1-homologous proteins were found to be the
7 most abundant transcripts in tobacco as well as wheat egg cells as well (Sprunck et al. 2005;
8 Ning et al. 2006; Zhao et al. 2011). The biochemical or molecular functions of ECA1
9 homologues are, however, not known yet. The EPS104 sequence with no annotation
10 represents a gene with similar expression properties. Therefore, these genes are good
11 candidates to isolate strong egg cell specific plant promoters that could potentially be used to
12 manipulate female fertility and/or parthenogenesis.

13 In addition to the annotated sequences, we have analyzed the expression of several ESTs that
14 code for hypothetical or unknown proteins. If the sequence/function of the represented genes
15 will be identified, e.g. following the whole genome sequencing of the wheat genome, it will
16 contribute to our knowledge about the molecular and cellular events underlying the first steps
17 of zygotic embryogenesis in plants.

18 The EST sequencing approaches has inherent drawbacks as they are relatively low
19 throughput, expensive and generally not quantitative. Establishing the exact inventory and
20 timing of fertilization-induced events in plants may be facilitated by the recent progress in
21 high throughput, quantitative, and cheaper RNA sequencing approaches (Schmidt et al.
22 2012a; Schmid et al. 2012b). The state of the art and the future potential of using these new
23 techniques in the analysis of plant gametophyte development have recently been reviewed by
24 Schmid et al. (Schmid et al. 2012b).

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References

- Baroux C, Autran D, Gillmor CS, Grimanelli D, Grossniklaus U (2008) The maternal to zygotic transition in animals and plants. *Cold Spring Harb Symp Quant Biol* 73:89-100
- Berckmans B, De Veylder L (2009) Transcriptional control of the cell cycle. *Curr Opin Plant Biol* 12:599-605
- Borg M, Brownfield L, Twell D (2009) Male gametophyte development: a molecular perspective. *J Exp Bot* 60:1465-1478
- Borg M, Twell D (2010) Life after meiosis: patterning the angiosperm male gametophyte. *Biochem Soc Trans* 38:577-582
- Feliciello I, Chinali G (1993) A modified alkaline lysis method for the preparation of highly purified plasmid DNA from *Escherichia coli*. *Anal Biochem* 212:394-401
- Götz S, García-Gómez JM, Terol J, Williams TD, Nagaraj SH, Nueda MJ, Robles M, Talón M, Dopazo J, Conesa A (2008) High-throughput functional annotation and data mining with the Blast2GO suite. *Nucleic Acids Res* 36:3420-3435
- Gray-Mitsumune M, O'Brien M, Bertrand C, Tebbji F, Nantel A, Matton DP (2006) Loss of ovule identity induced by overexpression of the fertilization-related kinase 2 (ScFRK2), a MAPKKK from *Solanum chacoense*. *J Exp Bot* 57:4171-4187
- Gupta PK, Mir RR, Mohan A, Kumar J (2008) Wheat genomics: present status and future prospects. *International journal of plant genomics* 2008:896451
- Kovács M, Barnabás B, Kranz E (1994) The isolation of viable egg cells of wheat (*Triticum aestivum* L.). *Sexual Plant Reprod* 7:311-312
- Kőszegi D, Johnston AJ, Rutten T, Czihal A, Altschmied L, Kumlehn J, Wüst SEJ, Kirioukhova O, Gheyselinck J, Grossniklaus U, Bäumllein H (2011) Members of the RKD transcription factor family induce an egg cell-like gene expression program. *Plant J* 67:280-291
- Kumlehn J, Lörz H, Kranz E (1999) Monitoring individual development of isolated wheat zygotes: a novel approach to study early embryogenesis. *Protoplasma* 208:156-162
- Kumlehn J, Kirik V, Czihal A, Altschmied L, Matzk F, Lörz H, Bäumllein H (2001) Parthenogenetic egg cells of wheat: cellular and molecular studies. *Sexual Plant Reproduction* 14:239-243
- Minami N, Suzuki T, Tsukamoto S (2007) Zygotic gene activation and maternal factors in mammals. *J Reprod Dev* 53:707-715
- Mishra NS, Tuteja R, Tuteja N (2006) Signaling through MAP kinase networks in plants. *Arch Biochem Biophys* 452:55-68

Ning J, Peng XB, Qu LH, Xin HP, Yan TT, Sun M (2006) Differential gene expression in egg cells and zygotes suggests that the transcriptome is restructured before the first zygotic division in tobacco. *FEBS Lett* 580:1747-1752

Nodine MD, Bartel DP (2012) Maternal and paternal genomes contribute equally to the transcriptome of early plant embryos. *Nature* 482:94-97

Ohnishi T, Takanashi H, Mogi M, Takahashi H, Kikuchi S, Yano K, Okamoto T, Fujita M, Kurata N, Tsutsumi N (2011) Distinct gene expression profiles in egg and synergid cells of rice as revealed by cell type-specific microarrays. *Plant Physiol* 155:881-891

Russell SD (1993) The Egg Cell: Development and Role in Fertilization and Early Embryogenesis. *Plant Cell* 5:1349-1359

Schmid MW, Schmidt A, Klostermeier UC, Barann M, Rosenstiel P, Grossniklaus U (2012a) A powerful method for transcriptional profiling of specific cell types in eukaryotes: laser-assisted microdissection and RNA sequencing. *PloS one* 7:e29685

Schmidt A, Schmid MW, Grossniklaus U (2012b) Analysis of plant germline development by high-throughput RNA profiling: technical advances and new insights. *Plant J* 70:18-29

Shen-Orr SS, Pilpel Y, Hunter CP (2010) Composition and regulation of maternal and zygotic transcriptomes reflects species-specific reproductive mode. *Genome Biol* 11:R58-R58

Singla B, Khurana JP, Khurana P (2008) Characterization of three somatic embryogenesis receptor kinase genes from wheat, *Triticum aestivum*. *Plant Cell Rep* 27:833-843

Sprunck S, Baumann U, Edwards K, Langridge P, Dresselhaus T (2005) The transcript composition of egg cells changes significantly following fertilization in wheat (*Triticum aestivum* L.). *Plant J* 41:660-672

Srilunchang KO, Krohn NG, Dresselhaus T (2010) DiSUMO-like DSUL is required for nuclei positioning, cell specification and viability during female gametophyte maturation in maize. *Development* 137:333-345

Sundaresan V, Alandete-Saez M (2010) Pattern formation in miniature: the female gametophyte of flowering plants. *Development* 137:179-189

Suzuki M, McCarty DR (2008) Functional symmetry of the B3 network controlling seed development. *Curr Opin Plant Biol* 11:548-553

Szűcs A, Dorjgotov D, Otvös K, Fodor C, Domoki M, Györgyey J, Kaló P, Kiss GB, Dudits D, Fehér A (2006) Characterization of three Rop GTPase genes of alfalfa (*Medicago sativa* L.). *Biochim Biophys Acta* 1759:108-115

Szűcs A, Jäger K, Jurca ME, Fábíán A, Bottka S, Zvara A, Barnabás B, Fehér A (2010) Histological and microarray analysis of the direct effect of water shortage alone or combined

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with heat on early grain development in wheat (*Triticum aestivum*). *Physiologia plantarum* 140:174-188

Tischner T, Kőszegi B, Veisz O (1997) Climatic programs used in the Martonvásár phytotron most frequently in recent years. *Acta Agron Hung* 45:85-104

Volz R, von Lyncker L, Baumann N, Dresselhaus T, Sprunck S, Gross-Hardt R (2012) LACHESIS-dependent egg-cell signaling regulates the development of female gametophytic cells. *Development* 139:498-502

Vrinten PL, Nakamura T, Kasha KJ (1999) Characterization of cDNAs expressed in the early stages of microspore embryogenesis in barley (*Hordeum vulgare*) L. *Plant Mol Biol* 41:455-463

Wuest SE, Vijverberg K, Schmidt A, Weiss M, Gheyselinck J, Lohr M, Wellmer F, Rahnenführer J, von Mering C, Grossniklaus U (2010) Arabidopsis female gametophyte gene expression map reveals similarities between plant and animal gametes. *Curr Biol* 20:506-512

Yang WC, Shi DQ, Chen YH (2010) Female gametophyte development in flowering plants. *Annu Rev Plant Biol* 61:89-108

Zhao J, Xin H, Qu L, Ning J, Peng X, Yan T, Ma L, Li S, Sun MX (2011) Dynamic changes of transcript profiles after fertilization are associated with de novo transcription and maternal elimination in tobacco zygote, and mark the onset of the maternal-to-zygotic transition. *Plant J* 65:131-145

Figure legends

Figure 1. Light and fluorescent micrographs of an unfertilized mature egg cell (A, B), one-celled zygotes (7 hours after fertilization; C, D) and bicellular pro-embryos (24 hours after fertilization; E, F).

Figure 2. The relative expression of genes selected based on their potential signaling/regulatory role during fertilization. A. The relative expression of the genes in various cell types/organs. Expression in the egg cell was chosen as a reference (relative expression=1). B. Relative expression of the genes in the egg cell. The TaUBC gene expression was chosen as a reference (relative expression=1). TaSERK3 was used as a positive control (Singla et al. 2008). Expression in the egg cell was normalized to the expression of the genes coding for a NADPH oxidase (TA61480_4565) and an ubiquitin conjugase (TA64564_4565). LEAF – young leaf; ANT- anther; OV- basal ovule part with synergids; the numbers indicate the time of isolation after fertilization in hours; EC – unfertilized egg cell; ZYG – zygote, isolated 7 hours after fertilization; ProE- bicellular proembryo, isolated 24 hours after fertilization. Average of relative gene expression values derived from three independent sampling, RNA isolation and cDNA synthesis is shown with standard errors.

Figure 3. The relative expression of genes represented by ESTs with no established homology to proteins with known function. A-D. The relative expression of the genes in various cell types/organs. Expression in the egg cell was chosen as a reference (relative expression=1). Genes are shown in separate histograms according to their expression pattern. E. Relative expression of the same genes in the egg cell. The TaUBC gene expression was chosen as a

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reference (relative expression=1). TaECA1 (homologous to HvECA1, Vrinten et al. 1999) and TaDSUL (Srilunchang et al. 2010) genes were used as positive controls for egg cell/zygote-specific expression. Expression in the egg cell was normalized to the expression of the genes coding for a NADPH oxidase (TA61480_4565) and an ubiquitin conjugase (TA64564_4565).

LEAF – young leaf; ANT- anther; OV- basal ovule part with synergids, the numbers indicate the time of isolation after fertilization in hours; EC – unfertilized egg cell; ZYG – zygote, isolated seven hours after fertilization; ProE- two-celled proembryo, isolated 24 hours after fertilization. Average of relative gene expression values derived from three independent sampling, RNA isolation and cDNA synthesis is shown with standard errors.

Table 1. Genes (TAs) with more than one representation among the sequenced ESTs

EGG CELLS			
PROBE_ID	LENGTH	BLAST HIT	OCCURENCES
EPS102	689	TA62694_4565 Putative OsCTTP	2
EPS109	293	TA64547_4565 Putative dihydroliipoamide dehydrogenase	7
EPS115	403	TA62221_4565 putative carbamoyl phosphate synthetase	2
EPS124	710	TA92976_4565 Armadillo/beta-catenin repeat protein-like	2
EPS133	579	TA57365_4565 GTP-binding nuclear protein Ran/	2
EPS136	690	CJ567765 Putative ubiquinone oxidoreductase subunit	3
EPS163	218	TA68893_4565 NME2 protein	2
EPS176	884	TA58264_4565 Glyceraldehyde-3-phosphate dehydrogenase, cytosolic 3	4
EPS181	509	TA57874_4565 40S ribosomal protein S8	2
EPS189	565	BJ289037 Ribosomal protein L18a-like	2
EPS246	109	CK208074 Ubiquitin C variant	2
EPS64	677	TA62564_4565 Ribosomal protein L15	2
ZYGOTES			
PROBE_ID	LENGTH	BLAST HIT	OCCURENCES
ZIG102	370	CJ623917 Ribosomal protein l34	2
ZIG107	487	TA56814_4565 Cytosolic heat shock protein 90	2
ZIG110	397	BJ283589 Hypothetical protein OJ1513_F02.133	2
ZIG119	626	BJ310704 Hypothetical protein	2
ZIG151	297	TA52896_4565 Ribosomal protein L35A	2
ZIG178	375	TA63131_4565 Hypothetical protein P0413G02.21	2
ZIG182	209	TA93140_4565	2
ZIG2	458	CJ590407 Cytosolic heat shock protein 90	5
ZIG217	287	TA59204_4565 26S proteasome regulatory particle non-ATPase subunit12	2
ZIG22	320	CK196860 Cytosolic glyceraldehyde-3-phosphate dehydrogenase	3
ZIG234	214	CJ570397 Disease-resistant-related protein	2
ZIG25	410	CD889724 Hypothetical protein OJ1513_F02.133	12
ZIG256	485	TA55830_4565 P0697C12.13	2
ZIG28	168	DN949012 40S ribosomal protein S28	2
ZIG311	630	TA63488_4565 60S ribosomal protein L17-1	2
ZIG36	233	CK194926 60s ribosomal protein L21	2
ZIG49	421	TA59714_4565 Hypothetical protein OJ1513_F02.133	5
ZIG5	468	TA60745_4565 Expressed protein	2
ZIG50	242	CD927088 Lactoylglutathione lyase	7
ZIG65	431	TA63098_4565	3
ZIG88	157	CK151631 T6D22.2	2

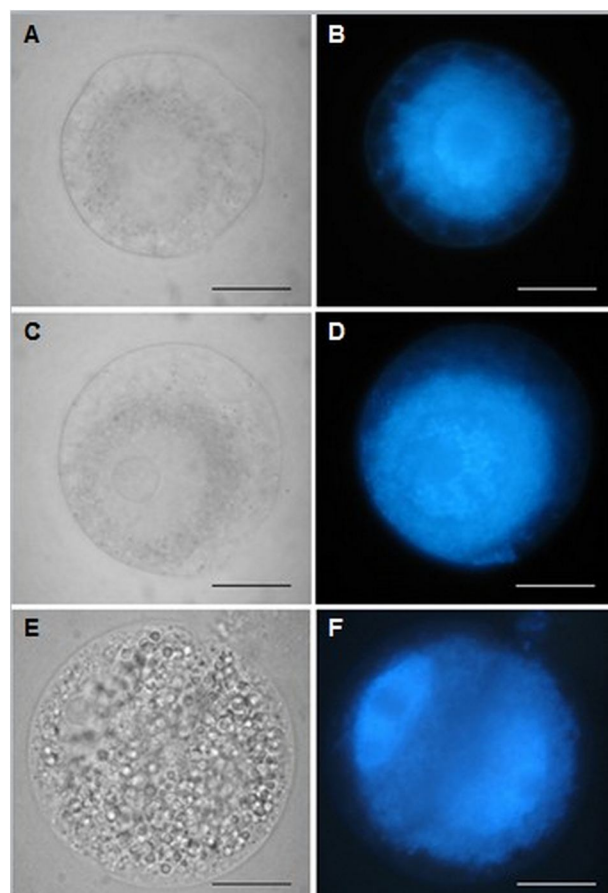


Fig.1.

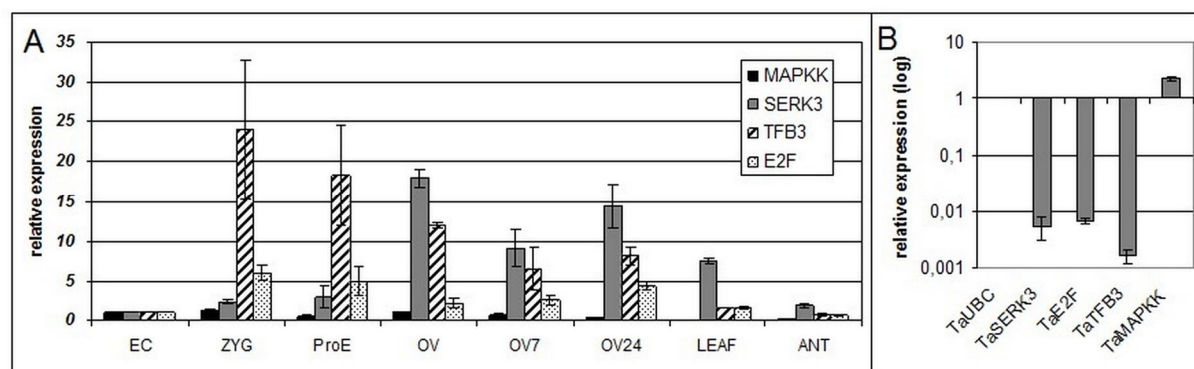


Fig.2

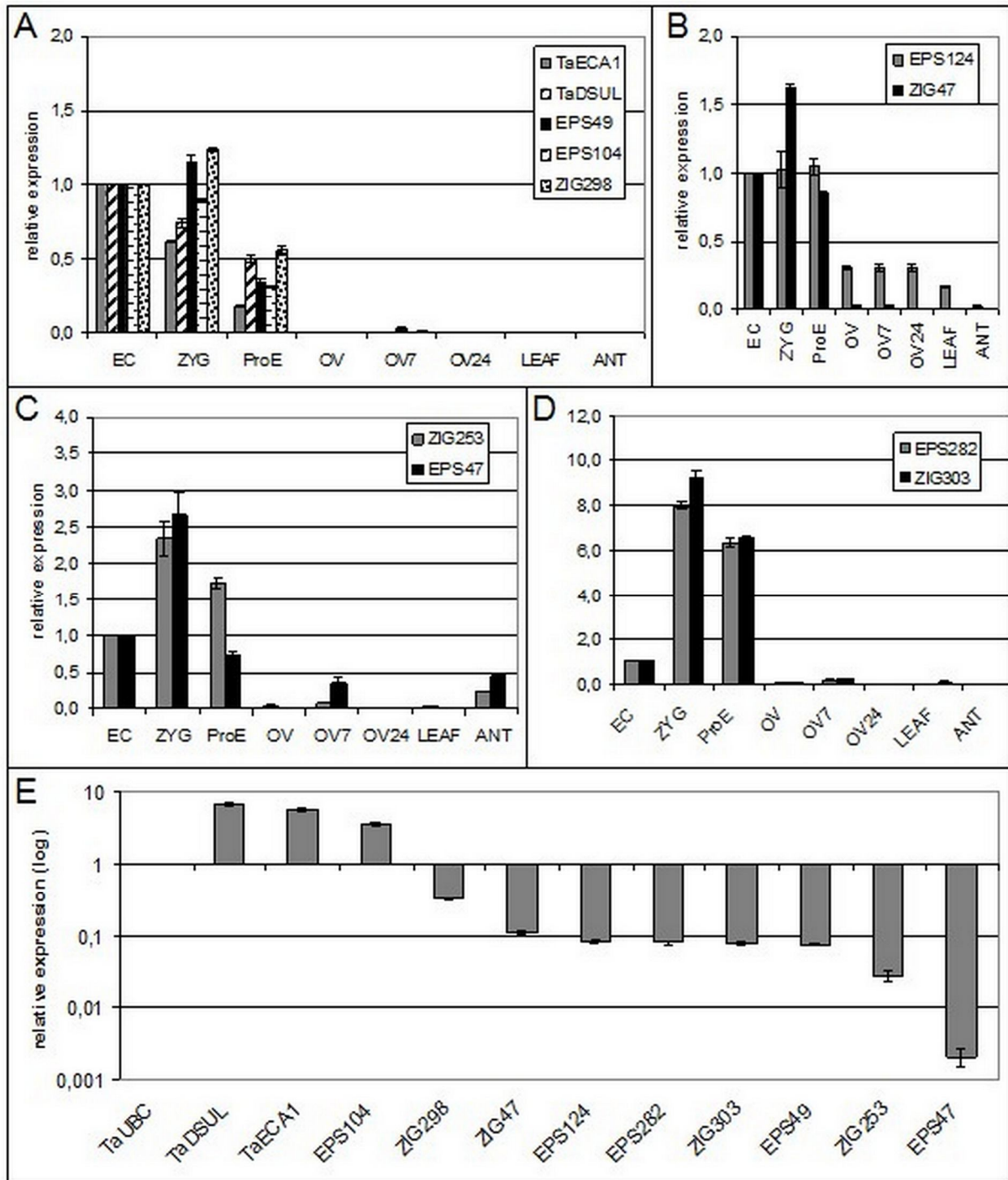


Fig.3.