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1 **Tissular specific inactivation by cytosine deaminase/uracil phosphoribosyl transferase as**
2 **a tool to study plant physiology**

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13 Running title: Tissue specific genetic ablation

14 **(1) SUMMARY**

15 Recent advances in the study of plant developmental and physiological responses have
16 benefited from tissue-specific approaches, revealing the role of some cell types in these
17 processes. Such approaches have relied on the inactivation of target cells using either toxic
18 compounds or deleterious genes. However, both tissue-specific and truly inducible tools are
19 lacking in order to precisely target a developmental window or specific growth response. We
20 engineered the yeast fluorocytosine deaminase (FCY1) gene by creating a fusion with the
21 bacterial uracil phosphoribosyl transferase (UPP) gene. The recombinant protein converts the
22 precursor 5-fluorocytosine (5-FC) into 5-fluorouracyl, a drug used in the treatment of a range
23 of cancers, which triggers DNA and RNA damage. We expressed the *FCY-UPP* gene
24 construct in specific cell types using enhancer trap lines and promoters demonstrating that this
25 marker acts cell autonomously. We also showed that it can inactivate slow developmental
26 processes like lateral root formation by targeting pericycle cells. It revealed a role for the
27 lateral root cap and the epidermis in controlling root growth, a faster response. The 5-FC
28 precursor acts systemically as demonstrated by its ability to inhibit stomatal movements when
29 supplied to the roots in combination with a guard cell specific promoter. Finally, we
30 demonstrate that the tissular inactivation is reversible and can therefore be used to
31 synchronize plant responses or determine cell type specific functions during different
32 developmental stages. This tool will greatly enhance our capacity to understand the respective
33 role of each cell type in plant physiology and development.

34 **(2) Significance statement**

35 Combining tissue specific-expression of cytosine deaminase and uracil phosphoribosyl
36 transferase and application of their precursor 5-fluorocytosine allows specific inactivation of
37 targeted tissues. This tool reveals a role for the lateral root cap and the epidermis in
38 controlling primary root growth and demonstrates to be acting in a tissue-specific and
39 reversible manner therefore opening the way to a better understanding of physiological and
40 developmental processes at the tissular and cellular level.

41 (3) INTRODUCTION

42 Plant physiological and developmental pathways rely on the coordinated action of several
43 tissues. Whether it is nutrient and water uptake by the root or light and CO₂ perception in the
44 shoot, understanding the respective role of each cell type is of primary importance. There are
45 now growing evidence that the ability of tissues to communicate, either adjacent or distant,
46 represents a key aspect of developmental processes. It is therefore becoming increasingly
47 important to study physiological and developmental pathways from a tissular and cellular
48 perspective. A key approach towards this goal has relied on the use of genetic ablation
49 methodologies. Placing a toxic gene under the control of a tightly regulated promoter can
50 selectively inactivate a cell type or group of cells and reveal their role in a complex tissue.
51 The diphtheria toxin A chain (DTA) is a potent inhibitor of translation that is toxic for plant
52 cells (Czako and An, 1991). Its targeted expression has been used for the past 25 years to
53 effectively reveal the role of several cell types (Thorsness *et al.*, 1993; Tsugeki and Fedoroff,
54 1999; Weijers *et al.*, 2003). Similar approaches based on genes triggering a general cellular
55 toxicity include expression of ribonuclease (Mariani *et al.*, 1990; Koltunow *et al.*, 1990;
56 Goldberg *et al.*, 1995). However, limitations of these tools are their constitutive activity and
57 their irreversible effects that can trigger early developmental defects, especially if placed
58 under a promoter whose expression is not limited in time and space. For example, such
59 approach induced the destruction of the root cap resulting in plants exhibiting strong growth
60 defect and subsequent death at an early stage (Tsugeki and Fedoroff, 1999). As a result, these
61 strategies have been confined to the study of flower and seed development (Day *et al.*, 1995;
62 Weijers *et al.*, 2003) since they have little effect on plant overall development.

63 A corrective strategy has consisted in the usage of regulatory elements from non-plant
64 organisms. Their specificity relies on the absence of an equivalent target in plants. These
65 heterologous elements include components regulated by the antibiotic tetracycline (Gatz *et*

66 *al.*, 1992), the synthetic steroid dexamethasone (Aoyama and Chua, 1997), IPTG (Wilde *et*
67 *al.*, 1992), ethanol (Roslan *et al.*, 2001) or the copper ion (Mett *et al.*, 1993). However, they
68 necessitate the combined use of two transgenes in plants: a transcription factor that acts as the
69 switch and a target promoter controlling the expression of the gene of interest. The number of
70 transgenes can go up to 3 if a reporter gene is included to follow the tissular specificity of the
71 induction (Deveaux *et al.*, 2003). Although this method allows for the choice of the target
72 gene to be induced, including a toxic gene, such as DTA or a nuclease, it increases the
73 complexity of the T-DNA(s) to be transferred and has not been widely used for genetic
74 ablation. Interestingly, the recent development of estradiol inducible transgenes with a full
75 suite of MultiSite Gateway compatible cell-type specific systems may lead to new
76 applications for genetic ablation studies (Brand *et al.*, 2006; Siligato *et al.*, 2016).

77 Instead of an inducible promoter, the genetic toxicity can be itself induced by relying on an
78 innocuous substance that is readily converted into a toxic compound by a transgenic
79 enzymatic activity. In plant, the use of the bacterial gene indole acetamide hydrolase (*iaaH*)
80 originating from the tumor inducing bacteria *Agrobacterium sp.* allows the conversion of the
81 inactive compound auxin indole acetamide into indole acetic acid. Large auxin accumulation
82 triggers general toxic effects, reminiscent of the use of 2,4 dichlorophenoxy acetic acid (2,4D)
83 as an herbicide. Similarly, the enzyme nitrate reductase (NR) can incorporate chlorate into the
84 toxic form chlorite (Nussaume *et al.*, 1991). The major limitation of these two markers is that
85 they are not cell autonomous since their end products can readily diffuse into the plant and
86 have therefore been used only as negative markers at the organism level (Klee *et al.*, 1987;
87 Nussaume *et al.*, 1991) and not for tissue specific studies.

88 Here, we report the use of an inducible system for genetic toxicity at the tissular level, based
89 on the heterologous expression of a tandem of two genes: fluorocytosine deaminase (FCY)
90 and uracil phosphoribosyl transferase (UPP). We demonstrate that tissue specific expression

91 of these genes is responsible for the incorporation of the 5-fluorocytosine (5-FC) precursor
92 that is normally not metabolized by higher eukaryotes and we use this system to inactivate
93 target cells or tissues. Tissue inactivation was found to be cell autonomous, acting on slow
94 and fast developmental and growth responses alike. Besides, its local and systemic reversible
95 range of action offers versatile opportunities for plant physiology studies.

96

97 **(4) RESULTS**

98 **Combination of exogenous 5-FC and FCY-UPP expression as a negative plant marker**

99 The antiprimidine effect of 5-fluorouracil (5-FU) has been largely described, mainly because
100 of its anticancer activity on mammalian cells (reviewed in Longley *et al.*, 2003). This drug
101 acts as an antimetabolite that inhibits synthetic processes (mainly targeting thymidylate
102 synthase, a key enzyme for DNA synthesis converting dUMP into dTMP). Concomitantly, it
103 is incorporated into nucleic acids, resulting in an altered cellular function mainly by blocking
104 RNA maturation (preRNA processing, tRNA post-transcriptional modifications and pre-
105 mRNA splicing). In this study, we used the 5-FU precursor 5-fluorocytosine (5-FC) since it is
106 inactive in plants due to lack of cytosine deaminase (FCY) activity (Figure 1a). Early work on
107 negative selection markers demonstrated that *in planta* expression of the yeast
108 (*Saccharomyces cerevisiae*) FCY gene under a constitutive promoter (35S) resulted in plants
109 sensitive to the exogenous application of 5-FC compared to wild-type controls (Perera *et al.*,
110 1993; Kobayashi *et al.*, 1995). Interestingly, concomitant expression of the *Escherichia coli*
111 uracil phosphoribosyl transferase (UPP) gene improves the cytotoxicity of the system by
112 enhancing the RNA incorporation pathway (Tiraby *et al.*, 1998 - Figure 1a). Indeed,
113 germination of seedlings on plates containing 1mM 5-FC had no effect on wild-type (Col-0)
114 plants whereas seedlings overexpressing the two genes in tandem (35S:FCY-UPP - Figure
115 1b) died rapidly a couple of days after germination (Figure 1c). When wild-type plants were

116 mixed with *35S:FCY-UPP* plants, the wild-type plants were not affected by the 5-FC
117 conversion into neighbouring transgenic plants, thereby demonstrating that the action of 5-FC
118 incorporation is plant autonomous (Figure 1c).

119 The toxic effect of 5-FC was shown to be concentration dependent in the independent
120 transgenic lines that we produced with a strong primary root growth reduction observed on
121 100 μ M 5-FC and a total arrest of seedling growth after germination at 500 μ M in line 1
122 whereas wild-type (Col-0) plants were unaffected (Figure 2a-c). Other commonly used
123 *Arabidopsis* ecotypes were also unaffected by a similar treatment (Figure S1a). A second line
124 showed a weaker sensitivity to 5-FC with a reduction observed at 250 μ M and a total growth
125 arrest at 1000 μ M (Figure S1b and c). The sensitivity of the plants to 5-FC correlated well
126 with the level of expression of the *FCY-UPP* transgene in these 2 independent lines (Figure
127 S1d).

128

129 **Tissue-specific expression of *FCY-UPP* drives tissue-autonomous toxicity**

130 In order to target 5-FC incorporation in specific tissues, we used the previously described
131 GAL4-based transactivation system (Brand and Perrimon, 1993). The *FCY-UPP* tandem
132 genes were fused and placed downstream the UAS (Upstream Activated Sequence). This
133 construction was transformed into the xylem pole pericycle cell specific J0121 line (Laplaze
134 *et al.*, 2005) whose expression starts in the elongation zone and is maintained in the
135 shootward direction up to the mature tissues (Figure 3a, b and c). Exogenous treatment with
136 5-FC had no effect on the untransformed J0121 plants whereas *J0121>>FCY-UPP* plants
137 showed a strong reduction in lateral root (LR) number (Figure 3d, e, f, and g). This toxic
138 effect on LR formation was found to be concentration dependent with a minimum effective
139 concentration of 1000 μ M and a total disappearance of LR formation at 2500 μ M 5-FC (Figure
140 3h). In order to determine whether primary root growth was also affected in this line, we

141 followed plant growth in real-time. A computer-controlled DSLR camera was used to take
142 pictures every 10 minutes for the duration of the experiment (setup shown in Figure S2a). No
143 difference in the growth of the control (non-treated) versus 5-FC plants was observed at
144 1000 μ M upon 70 hours after transfer, therefore demonstrating the tissue autonomous nature
145 of the inactivation system (Figure 3i). However, at higher 5-FC concentrations (2500 μ M and
146 above) primary root growth was also affected (Figure S2b) demonstrating that tissue
147 autonomy can be overcome at higher 5-FC treatments. Primary root growth of wild-type
148 plants remained unaffected by a similar treatment (Figure S2c). In order to determine whether
149 lateral root initiation or subsequent primordium emergence is altered by 5-FC treatment of the
150 the *J0121>>FCY-UPP* plants, we determined the ratio of emerged and non-emerged lateral
151 roots. The treatment did not decrease the number of initiation events but significantly reduced
152 the emergence of lateral root primordium compared to untreated plants (Figure S2d). The
153 expression pattern driven by the J0121 line remained unaltered by 5-FC treatment (Figure
154 S3a-b and d-e) and blocked lateral root primordium seemed similar to those of untreated
155 plants (Figure S3c and f).

156

157 **Fast growth responses are impacted by 5-FC incorporation toxicity**

158 The toxic effect of 5-FC incorporation into the pericycle on LR formation (a slow
159 developmental process) prompted us to test whether the system could also affect faster growth
160 responses. We transformed the *UAS:FCY-UPP* construct into the lateral root cap and
161 epidermis specific J0951 line (Figure 4a and b). Treatment with 5-FC resulted in arrested
162 primary root growth in the treated versus non-treated *J0951>>FCY-UPP* line (Figure 4c and
163 d). This effect was found to be 5-FC concentration dependent with a minimum effective
164 concentration tested at 100 μ M (Figure S4a and b). Real-time tracking of primary root growth
165 revealed that 5-FC altered growth *ca.* 48 hours after transfer on the 5-FC medium versus

166 control plants transferred on a regular medium (Figure 4e). Root growth was not totally
167 abolished but reduction was drastic. A quicker effect was obtained on the constitutive
168 *35S:FCY-UPP* lines (Figure S4c,d), the stronger expression level (Figure S1d) correlated with
169 a quicker response (down to 18 and 30 hours). The expression pattern driven by the J0951
170 line remained unaltered by 5-FC treatment (Figure S5a-d).

171

172 **The FCY-UPP-GFP protein fusion is cell autonomous**

173 In order to determine whether the FCY-UPP protein is able to move across cells, we fused it
174 to the GFP reporter and expressed it under the control of the epidermis-specific WEREWOLF
175 promoter region. In comparison with the direct *pWER:GFP* fusion that displays GFP
176 fluorescence in the epidermis (Figure 5b), the expression pattern of the *pWER:FCY-UPP-*
177 *GFP* construct was strictly identical (Figure 5d). Treatment with 5-FC did not alter the
178 expression profile driven by the 2 constructs (Figure 5c,e,f). Attaching the GFP protein to the
179 FCY-UPP tandem did not prevent its enzymatic function, dose response treatment of this line
180 with 5-FC triggered primary root growth arrest at concentrations above 1000 μ M (Figure 5a
181 and S6).

182

183 **5-FC systemically diffuses into plants from root to leaves to exert its toxic incorporation** 184 **effect**

185 Since 5-FC is efficiently incorporated by FCY-UPP when the tandem genes are expressed in
186 roots, we wanted to test whether expression in the distal parts of the plants would still be
187 efficient. In the absence of available catalogues of enhancer trap lines in the shoot, we directly
188 fused the *FCY-UPP* genes to the guard cell specific promoter of the *MYB60* gene. This
189 promoter drives expression specifically in the guard cells as shown by the *pMYB60* promoter
190 fusion with the glucuronidase gene (*pMYB60:GUS* – Figure 6a, b and c). We measured

191 stomatal aperture as a response to dark-light transition in sand/hydroponic cultivated plants.
192 5-FC was applied directly to the root system 24 hours prior to stomatal aperture measurement.
193 Both *35S:FCY-UPP* and *pMYB60:FCY-UPP* lost the ability to open their stomata upon
194 100 μ M 5-FC application. Identical results were obtained in 2 independent *pMYB60:FCY-*
195 *UPP* lines with similar expression levels (Figure S7a). Stomatal aperture controls water loss
196 from the leaves, which in turn regulates leaf surface temperature. We monitored surface leaf
197 temperature with a thermal camera to determine whether 5-FC treatment in *pMYB60:FCY-*
198 *UPP* plants affected plant transpiration. A *ca.* 2 $^{\circ}$ C increase in leaf temperature was observed
199 in the 5-FC treated *pMYB60:FCY-UPP* plants compared to controls, untreated and 5FC-
200 treated Col-0 plants demonstrating the absence of effect of 5-FC on leaf temperature in the
201 wild-type and a strong reduction of leaf transpiration in the transgenic line as a result of
202 stomatal closure (Figure 6e). Total leaf area was not affected by 5-FC treatment and was not
203 different across the control and transgenic lines (Figure S7b).

204

205 **5-FC incorporation toxicity is reversible**

206 The toxicity triggered by tissue specific incorporation of 5-FC strongly impacts processes like
207 LR formation, primary root growth and stomatal aperture. We tested whether these effects are
208 permanent or reversible. Removal of 5-FC by transfer to a regular medium was performed on
209 the J0121>>FCY-UPP line. Plants were grown for 9 days after germination on a medium
210 containing 1000 μ M 5-FC and then transferred to a medium without any 5-FC. Plants from 2
211 independent J0121>>FCY-UPP transgenic lines were able to produce as many lateral roots 3
212 days after transfer back to the control medium compared to wild-type Col-0 controls (Figure
213 7a). We next tested the reversibility of 5-FC incorporation on stomatal aperture regulation.
214 Plants were grown for 25 days and then placed in the presence of 100 μ M 5-FC for 24 hours.
215 Plants expressing the two transgenes specifically in the guard cells (*pMYB60:FCY-UPP*) were

216 unable to open their stomata in response to dark/light transition. After transfer back to
217 hydroponic solution deprived of 5-FC for 48 hours, the plants from 2 *pMYB60:FCY-UPP*
218 lines regain the ability to respond to dark/light transition and open their stomata (Figure 7b),
219 therefore demonstrating the reversible effect of 5-FC incorporation.

220

221 **(5) DISCUSSION**

222 Early work identified that cytosine deaminase (FCY) activity produced by prokaryotes but not
223 higher eukaryotes could be used as a negative marker together with its substrate 5-
224 Fluorocytosine (5-FC). The deamination 5-FC by FCY into cytotoxic 5-Fluorouracil (5-FU)
225 has been used in the model plant *Arabidopsis* as a negative selection marker under the
226 constitutive and strong viral 35S promoter (Perera *et al.*, 1993; Kobayashi *et al.*, 1995).
227 Similar results have been reported in rice (Dai *et al.*, 2001) and tomato (Hashimoto *et al.*,
228 1999). These studies have shown that 5-FC incorporation triggers plant autonomous toxicity,
229 whereas other negative markers such as *iaaH* (using IAM as a precursor) or *NR* (using
230 chlorate as a substrate) can be toxic for neighbouring plants due to diffusion of their toxic
231 product in the culture medium. Subsequently, the concomitant expression of the bacterial
232 gene uracil phosphoribosyltransferase was shown to improve dramatically the sensitivity of
233 mammalian cells to 5-FC (Tiraby *et al.*, 1998). The fast metabolic incorporation of 5-FC into
234 its product suggested a passive diffusion of extracellular 5-FC through the plasma membrane,
235 resulting in increased drug uptake. In this study, we fused the yeast version of FCY and the
236 bacterial version of UPP to create a functional protein tandem with elevated activity in plants.
237 In order to achieve tissular specificity of 5-FC incorporation, we placed this chimeric protein
238 under the expression of various tissue-specific promoters, including the yeast UAS activating
239 sequence to benefit from the available transactivation lines (Laplaze *et al.*, 2005). Our results
240 demonstrated that the tandem expression of FCY-UPP protein retains its plant autonomous

241 properties and that the toxicity did not spread across the culture medium (Figure 1c). In order
242 to further characterize the tissue specificity of the FCY-UPP tandem, we expressed it in the
243 xylem pole pericycle cells from which lateral roots are being formed (Dubrovsky *et al.*,
244 2000). In the J0121 enhancer trap line driving FCY-UPP expression, 1mM 5-FC application
245 can block selectively LR formation without impacting primary root growth therefore
246 suggesting that 5-FC metabolites do not diffuse to adjacent tissues where they would
247 otherwise block cellular growth. Indeed, expressing FCY-UPP in the lateral root cap and
248 epidermis using the J0951 enhancer trap line resulted in a strong reduction of primary root
249 growth. Similarly, when FCY-UPP proteins were expressed in the guard cells using the
250 pMYB60 promoter, no reduction in total leaf area was observed. These observations suggest
251 that both the FCY-UPP tandem protein and the products of 5-FC incorporation remain in the
252 cells where the construct is expressed at least on a short timescale. We observed a tagged
253 version of FCY-UPP fused to the GFP reporter and expressed under the epidermis specific
254 promoter of *WEREWOLF* (Lee and Schiefelbein, 1999) compared to a direct pWER:GFP
255 fusion. Both expression profiles were strictly identical and unaffected by 5-FC treatment
256 (Figure 5b-f) demonstrating that the FCY-UPP-GFP protein acts cell autonomously. Similar
257 use of the FCY-UPP tandem proteins proved to be toxic in animal systems with a high level
258 of specificity to fight lung cancer in mice (Christensen *et al.*, 2010) and rat (Johnson *et al.*,
259 2011), however no report has been made on the ability of the tandem protein to be transported
260 across animal cell membranes. Inactivating shoot tissues can be challenging since they are not
261 in direct contact with the culture medium and spraying chemicals can lead to heterogeneous
262 applications. In the case of 5-FC applications, we were able to feed the plants from the root
263 and still observe a long-distance effect demonstrating that 5-FC is systemically transported.
264 Indeed, by placing the FCY-UPP proteins under the control of the guard cell specific
265 promoter pMYB60, we were able to specifically block stomatal aperture by feeding the root

266 with 5-FC. Reversibility is a key advantage of an inducible inactivation system because it
267 opens the way to synchronisation experiments where the experimenter can block the activity
268 of a tissue for a certain amount of time and then release it across several individuals.
269 Surprisingly, the toxicity of the 5-FC products was not so strong that it irreversibly killed the
270 cells. We can hypothesize that blocking RNA metabolism exerted a negative feedback on the
271 production of the FCY-UPP proteins themselves, therefore preventing a too strong toxicity.
272 Although this is pure speculation, further work will be needed to fully quantify this effect.
273 Despite the tissue specific FCY-UPP system being a great tool to inactivate cell in a precise
274 spatial and temporal manner, there are some limitations. First of all, the availability of a
275 promoter with the desired expression pattern is a requirement and generation of transgenic
276 plant is necessary. However, since it is an inducible system, early (embryonic) expression
277 profiles of the promoter of choice is not problematic. Secondly, the range of active 5-FC
278 concentrations is fairly high (from 100 to 1000 μ M depending on the lines tested here) this
279 may be related to the necessity to reach an active dose in distant tissues. But this is not a
280 major issue considering the relatively cheap price of 5-FC. These two limitations do not
281 overcome the great advantages of a tool that is tissue specific, cell autonomous, reversible and
282 acts at long distance. Future work using this tool should lead to a better understanding of the
283 respective role of various tissues in more complex responses involving cell-to-cell
284 communication or high levels of synchronisation across complex organs.

285

286 **(6) EXPERIMENTAL PROCEDURES**

287 **Vector construction**

288 *FCY1* from *Saccharomyces cerevisiae* and *UPP* genes from *Escherichia coli* were PCR
289 amplified using DNA extracts from corresponding organism (FCY1-F
290 5'GGGACAAGTTTGTACAAAAAAGCAGGCTTAATGGTGACAGGGGGAATG3');

291 FCY-R 5'TCCACGATCTTCATCTCACCAATATCTTCAA3'; UPP-F
292 5'AAGATATTGGTGAGATGAAGATCGTGGAAGTC3'; UPP-R
293 5'GGGGACCACTTTGTACAAGAAAGCTGGGT-CTTTCGTACCAAAGATTTT3'). PCR
294 products were fused and cloned into pDONR207 by BP Gateway reaction to create pEN207
295 FCY-UPP. pEN207 FCY-UPP was used in a multisite Gateway LR reaction (Karimi *et al.*,
296 2007) with the destination vector pB7m34GW and pEN-UAS (from VIB Department
297 gateway.psb.ugent.be) to generate the *UAS:FCY-UPP* construct. *FCY-UPP* was also
298 subsequently transferred from pEN207 FCY-UPP into Gateway compatible pMDC32 vector
299 containing 2X35S promoter or *AtMYB60* minimal promoter, *proAtMYB60*₂₃₂, which was
300 cloned using the HindIII–BamHI sites. A 2.4kb sequence upstream of ATG from the
301 *WEREWOLF* gene (*At5g14750*) was PCR amplified using primers containing an HindIII
302 restriction site (pWER-F: 5'TCTAAGCTTAAACCCGAATCATCATGCAAT3' and pWER-
303 R 5'TCTAAGCTTTCTTTTTGTTTCTTTGAATGA5') and subsequently cloned into a
304 pGWB4 plasmid containing the ER-targeted GFP as a C-terminal cassette to create pWER4.
305 Development of Series of Gateway Binary Vectors, pGWBs, for Realizing Efficient
306 Construction of Fusion Genes for Plant Transformation. J Biosci. Bioeng). The pWER4
307 plasmid was used in a multisite Gateway LR reaction (Karimi *et al.*, 2007) as a destination
308 vector with pEN207 FCY-UPP to create pWER:FCY-UPP-GFP. Constructs were transformed
309 into the relevant genetic background by floral dipping and homozygous T3 lines were
310 generated by selfing.

311

312 **Plant material and growth**

313 Seeds for the following lines were obtained from the Nottingham Arabidopsis Stock Centre
314 (NASC): Col-0, J0121 (Laplaze *et al.*, 2005) and J0951 (Swarup *et al.*, 2005). For *in vitro*
315 culture, plants were grown on vertical half MS plates at 23°C under long days (16h light at

316 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). For hydroponic culture, plants were grown in a controlled environment
317 (8 h photoperiod at 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, 21 °C, and 70% relative humidity) in a nutrient
318 solution (800 mM $\text{Ca}(\text{NO}_3)_2\cdot 4\text{H}_2\text{O}$; 2 mM KNO_3 ; 1.1 mM $\text{MgSO}_4\cdot 7\text{H}_2\text{O}$; 60 mM K_2HPO_4 ;
319 700 mM KH_2PO_4 ; 20 mM $\text{FeSO}_4\cdot 7\text{H}_2\text{O}$; 20 mM Na_2EDTA , 2H₂O; 75 nM $(\text{NH}_4)_2\text{MoO}_7\cdot 2\text{H}_2\text{O}$;
320 4H₂O; 3.5 mM $\text{MnSO}_4\cdot \text{H}_2\text{O}$; 3 mM $\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$; 9.25 mM H_3BO_3 ; 785 nM $\text{CuSO}_4\cdot 5\text{H}_2\text{O}$;
321 final pH 5.8). The germination of surface-sterilized seeds was carried out in half MS plates.
322 For hydroponic cultures, the plantlets were transferred on sand after 2 weeks on vertical
323 plates, left there for an additional week period, and finally transferred to a home-built
324 hydroponic culture setup. 5-FC (ref. F7129 Sigma-Aldrich) was diluted in water at the
325 concentration of 10mM and subsequently aliquoted to avoid freeze-thaw cycles that quickly
326 denature the product (loss of activity).

327

328 **Real-time root growth tracking**

329 Photographic images were acquired every 10 minutes under continuous light with a Canon
330 EOS 700D reflex camera controlled by the EOS Utility software. The software was set such
331 that the camera parameters, such as focus, aperture, and exposure time, remained constant
332 between exposures. Plates were arranged to minimize reflection from the overhead lights.
333 Primary root length was determined on the image series using RootTrace (French *et al.*, 2009)
334 that allows rapid acquisition of growth parameter. Image acquisition was started upon transfer
335 of the plants to a new medium (control or 5-FC treated). Regular primary root length
336 measurements were performed on single images using ImageJ software equipped with the
337 NeuronJ plugin.

338

339 **Stomatal aperture scoring**

340 The abaxial side of leaves of 4- to 5-week-old Arabidopsis plants was stuck on coverslips and

341 peeled. Peels were submersed in petri dishes containing 10 mM MES/Tris, pH 6.0, and 30
342 mM KCl at 23°C. To test the effect of 5-FC, peels were first kept for 30 min in darkness and
343 then transferred in the same buffer supplemented with 10 or 100 mM ABA or the equivalent
344 dose of ethanol for 2 h under light (250 mmol.m⁻².s⁻¹). Ethanol used for ABA solutions did
345 not exceed 0.1% (v/v) final concentration. Stomatal apertures were measured with an optical
346 microscope (Nikon; Optiphot) fitted with a camera lucida and a digitizing table (Houston
347 Instrument) linked to a computer as described (Leonhardt *et al.*, 1997). Each data point
348 represented the mean of at least 80 stomatal apertures. Each experiment was repeated at least
349 twice.

350

351 **Leaf temperature probing**

352 Thermal imaging of 5-FC treated plantlets was performed as described previously (Merlot *et*
353 *al.*, 2002). In brief, plants were first grown under hydroponic conditions for 3 weeks. Then
354 100µM 5-FC was added during 24h. Thermal images were obtained using a Thermacam
355 infrared camera (FLIR A655sc 25°, 50Hz). Images were saved and analysed on a personal
356 computer using the ResearchIR4 Max Software provided by FLIR.

357

358 **Histochemical analysis and microscopy**

359 GUS staining was done as previously described (Péret *et al.*, 2007). Plants were cleared for 24
360 h in 1M chloral hydrate and 33% glycerol. Seedlings were mounted in 50% glycerol and
361 observed with an optical Leica LDM600 microscope. For confocal microscopy, plants were
362 stained with 10 mg.ml⁻¹ propidium iodide for 30 s and images were captured with an inverted
363 confocal laser-scanning microscope (Leica TCS SP2).

364

365 **(7) Accession numbers;**

366 FCY1 : NCBI GeneID 856175; UPP : NCBI GeneID: 946979

367

368 **(8) Acknowledgements;**

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370 11-PDOC-003-01 grant to BP).

371

372 **(9) Short legends for Supporting Information;**

373 Supporting figures: Figure S1, Figure S2, Figure S3, Figure S4, Figure S5, Figure S6, Figure
374 S7.

375

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474

475 **(11) Tables;**

476 N/A

477

478 **(12) Figure legends;**

479 **Figure 1.** 5-fluorocytosine incorporation by cytosine deaminase generates cellular toxicity.

480 (a) 5-FC is incorporated into 2 distinct pathways leading to RNA and DNA damage.

481 Concomitant expression of uracil phosphoribosyl transferase favors the RNA damage

482 pathway. (b) In this study, we fused the FCY and UPP gene to express them in tandem under

483 the regulation of various promoters such as 35S for constitutive expression, the upstream-

484 activated sequence (UAS) for transactivation by GAL4 and the guard cell specific promoter

485 *pMYB60*. (c) Wild-type (Col-0) and *35S:FCY-UPP* seedlings were germinated on plates in the

486 absence (Non-Treated) or presence (5-FC) of 500 μ M 5-fluorocytosine (n>80).

487

488 **Figure 2.** Dose-dependent 5-FC toxicity on primary root growth.

489 (a-c) Seedlings were germinated on growing concentrations of 5-fluorocytosine (0, 100, 250,
490 500, 1000 and 2500 μM) and primary root length was measured (data represent mean \pm sem,
491 $n=20$). Asterisks indicate a significant difference with corresponding non-treated control
492 experiment by Student's t-test (* $P<0.001$; $n=10$). Bars are 1,5mm.

493

494 **Figure 3.** *FCY-UPP* expression in the pericycle blocks lateral root formation upon 5-FC
495 application.

496 (a-c) The J0121 transactivation line triggers GFP expression in the xylem pole pericycle cells
497 starting from the elongation zone (a), up to the mature part of the root (b) and including stage I
498 lateral root primordium (c). (d-g) 6 day-old wild-type (Col-0) seedlings germinated on control
499 (d) or 1000 μM 5-fluorocytosine medium (e) and *J0121>>FCY-UPP* seedlings germinated on
500 control (f) or 1000 μM 5-fluorocytosine medium (g). (h) Plant lateral root density (number of
501 emerged lateral roots per cm of primary root length) was scored 6 days after germination for
502 various 5-FC concentrations (0, 100, 250, 500, 1000, and 2500 μM). (i) Real-time primary
503 root growth tracking of non-treated (control) versus 1000 μM 5-fluorocytosine treated (5-FC)
504 seedlings for 70 hours after transfer. Both curves overlap (data represent mean \pm sem, $n=10$).
505 Similar real-time tracking of non-transformed J0121 control line is shown as an insert.
506 Asterisks indicate a significant difference with corresponding non-treated control experiment
507 by Student's t-test (* $P<0.001$; $n=10$). Bars are 40 μm (a,b), 15 μm (c) and 3mm (d-g).

508

509 **Figure 4.** Tissular inactivation of the lateral root cap and epidermis blocks primary root
510 growth.

511 (a-b) The J0951 transactivation line triggers GFP expression in the lateral root cap cells (a)
512 and the epidermis (b). (c-d) 6 day-old *J0951>>FCY-UPP* seedlings germinated on control (c)

513 or 500 μ M 5-fluorocytosine medium (d). (e) Real-time primary root growth tracking of non-
514 treated (control) versus 500 μ M 5-fluorocytosine treated (5-FC) seedlings for 130 hours after
515 transfer (data represent mean \pm sem, n=10). Similar real-time tracking of non-transformed
516 J0951 control line is shown as an insert. Bars are 40 μ m (a,b) and 5mm (c,d).

517

518 **Figure 5.** FCY-UPP-GFP protein is expressed in a cell autonomous manner.

519 (a) Plants containing the expression marker *pWER:GFP* or the functional *pWER:FCY-UPP-*
520 *WER* fusion after no treatment (Control) or 500 μ M 5-fluorocytosine treatment (5-FC) at 6
521 days after germination. (b-f) Laser-scanning confocal microscope image of epidermal
522 expression similarly driven by these 2 lines : *pWER:GFP* (b-c) and *pWER:FCY-UPP-WER*
523 (d-f) after no treatment (Control) or 500 μ M 5-fluorocytosine treatment (5-FC). (f) Zoom on
524 epidermal expression in the *pWER:FCY-UPP-WER* line despite 5-FC induced morphological
525 changes. Bars are 2mm (a) and 15 μ m (b-f).

526

527 **Figure 6.** Systemic action of 5-FC incorporation blocks stomatal aperture and leaf
528 temperature regulation

529 (a-c) *pMYB60:GUS* expression pattern in leaves and guard cells. (d) Stomatal aperture was
530 measured on wild-type (Col-0), *35S:FCY-UPP* and *pMYB60:FCY-UPP* (2 independent lines)
531 plants in the non-treated (control), DMSO treated and 100 μ M 5-FC treated conditions (data
532 represent mean \pm sem, n=3). (e) False colour infrared image of plants treated or not with
533 100 μ M 5-FC during 24h indicate temperature level according to scale on the right. Asterisks
534 indicate a significant difference with corresponding control experiment by Student's t-test (*
535 P<0.05). Bars are 200 μ m (a), 60 μ m (b), 20 μ m (c) and 20 mm(e).

536

537 **Figure 7.** Tissue inactivation resulting of 5-FC incorporation is reversible.

538 (a) Lateral root density (number of roots per cm of primary root) was determined on wild-type
539 (Col-0) and J0121>>FCY-UPP plants (2 independent lines) 6 days after germination on
540 regular medium (Control - white bars) or 1000 μ M 5-FC medium (5-FC - grey bars) and after
541 9 days on 5-FC medium and transfer for 3 days on a regular medium (+3 Control - black
542 bars). (b) Stomatal aperture was measured on wild-type (Col-0), *35S:FCY-UPP* and
543 *pMYB60:FCY-UPP* (2 independent lines) plants in the non-treated (Control), 100 μ M 5-FC
544 treated and 2 days after transfer back to non-treated conditions (data represent mean
545 \pm sem, n=2). Asterisks indicate a significant difference with corresponding control experiment
546 by Student's t-test (* P<0.05).

Figure 1

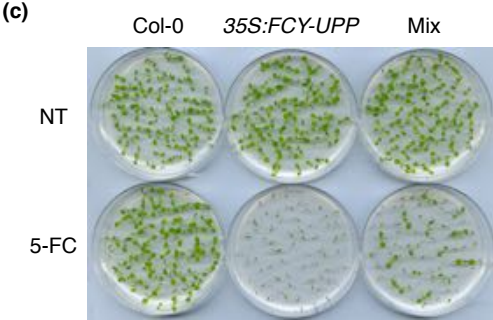
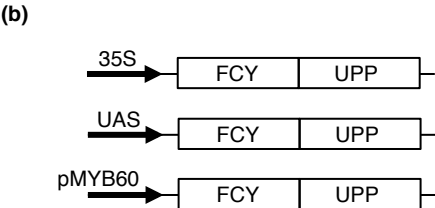
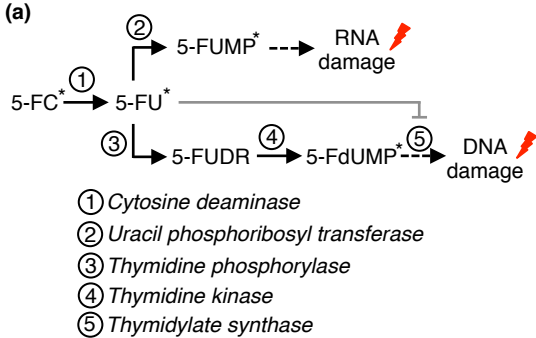


Figure 2

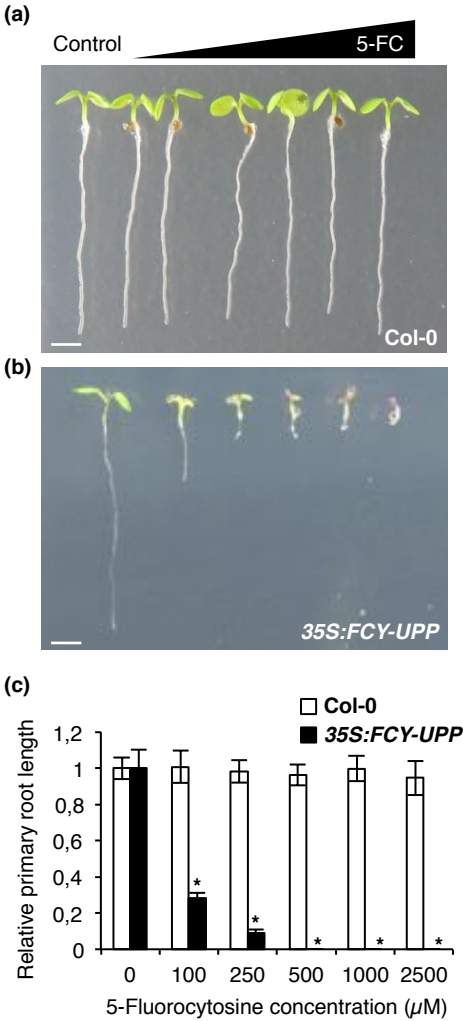


Figure 3

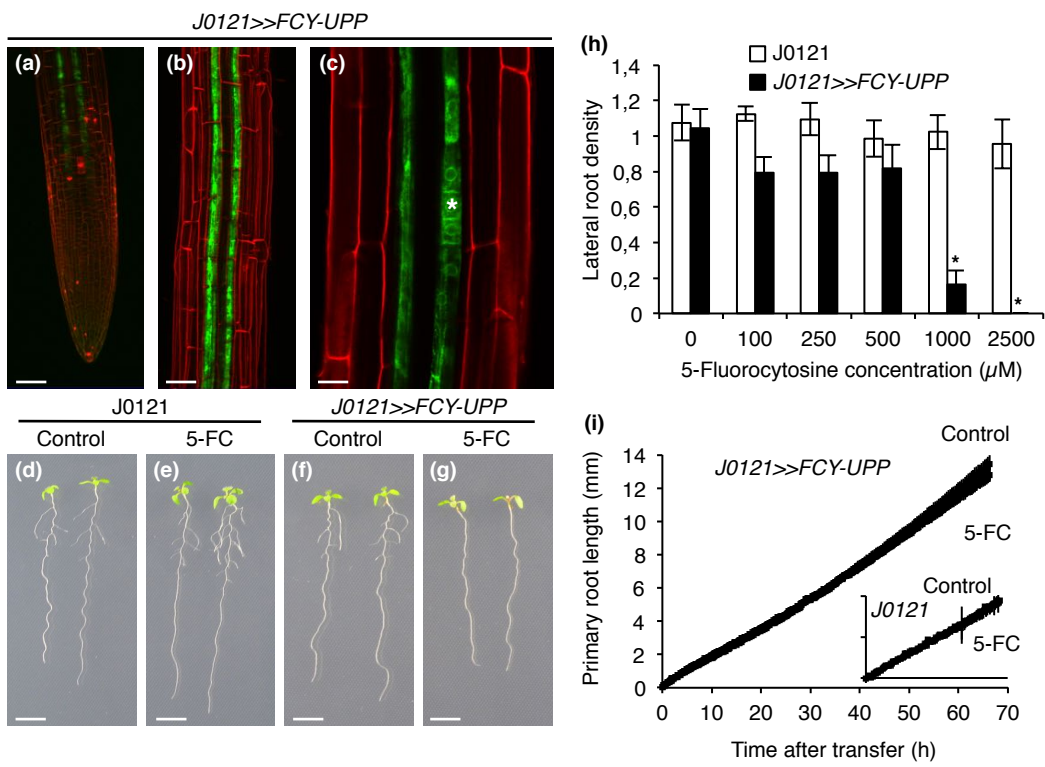


Figure 4

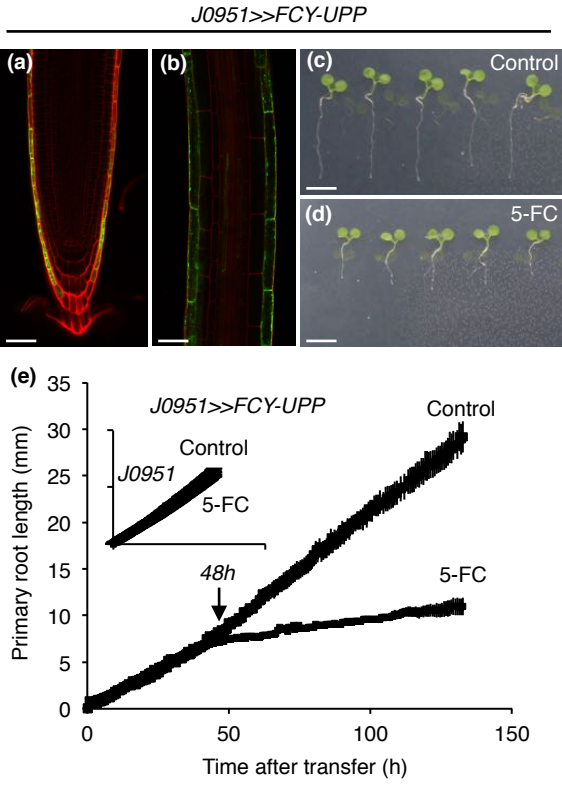


Figure 5

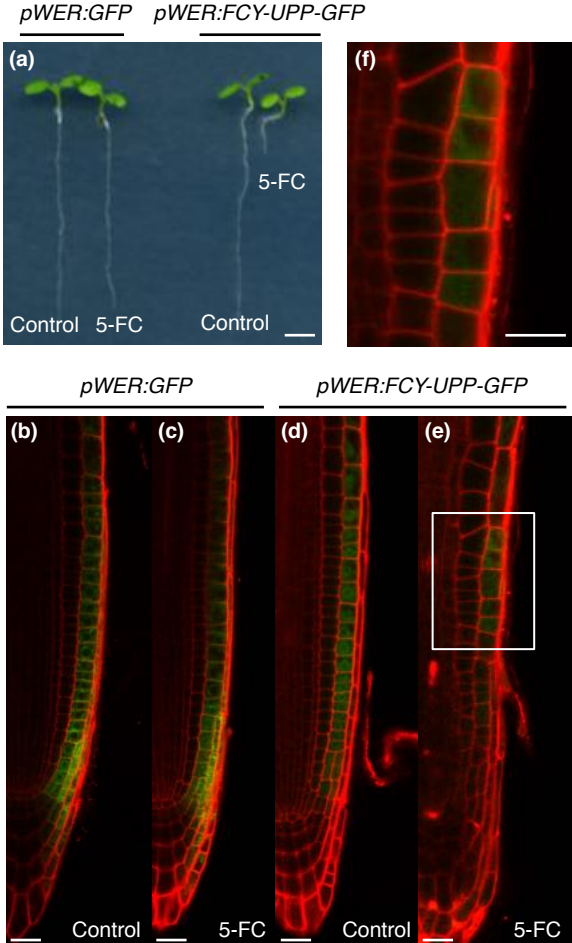


Figure 6

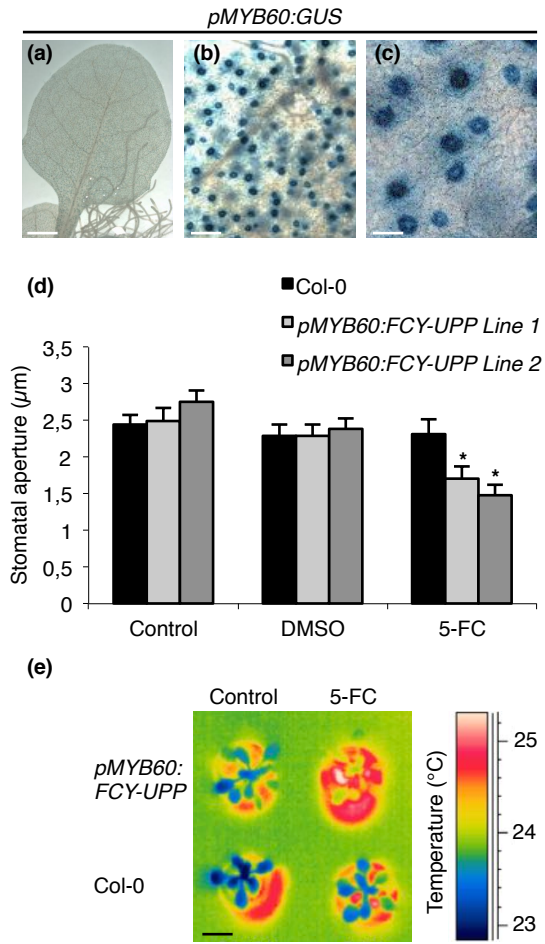


Figure 7

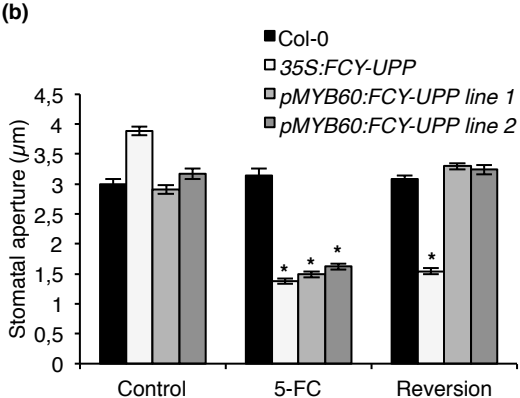
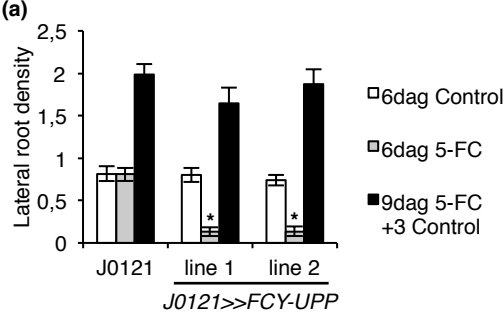


Figure S1

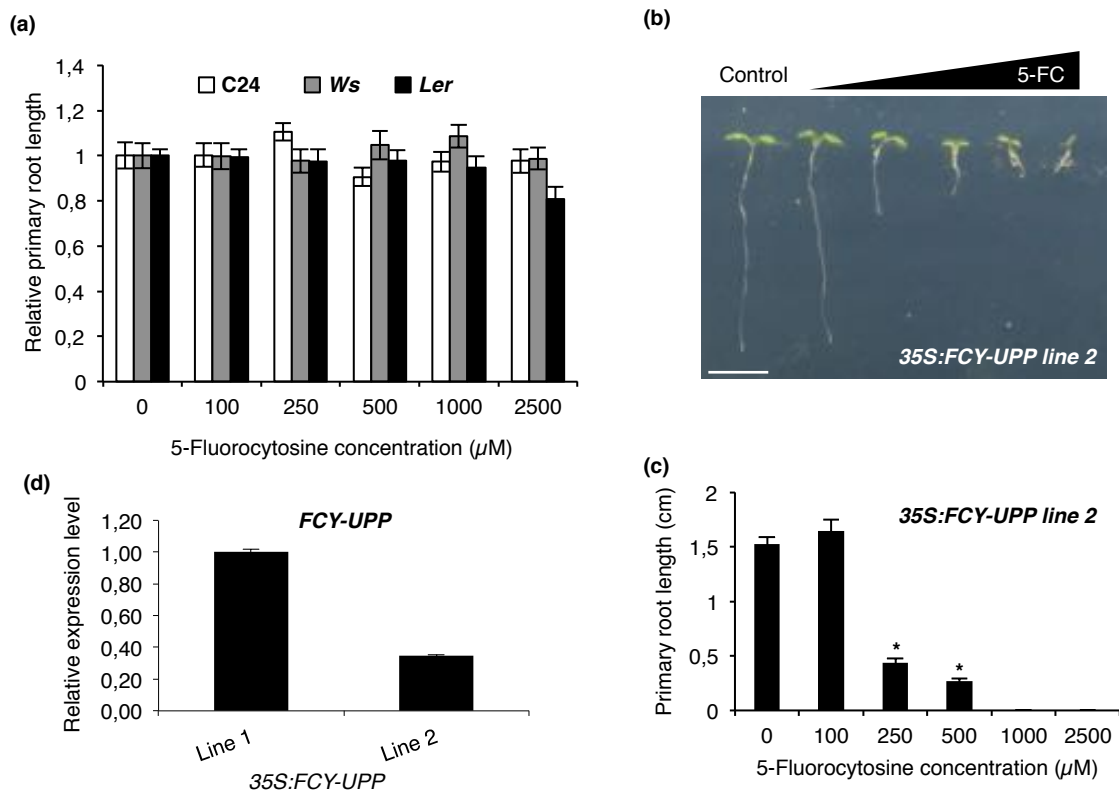


Fig. S1. Effect of 5-FC treatment on various ecotypes and independent 35S:FCY-UPP transgenic line with lower expression level of the transgene

(a-c) Seedlings were germinated on growing concentrations of 5-fluorocytosine (0, 100, 250, 500, 1000 and 2500 μM) and primary root length was measured ($n=20$). (d) Relative expression level of the *FCY-UPP* RNA determined by quantitative PCR. Asterisks indicate a significant difference with corresponding control experiment by Student's t-test (* $P<0.001$; $n=10$). Bar is 5mm.

Figure S2

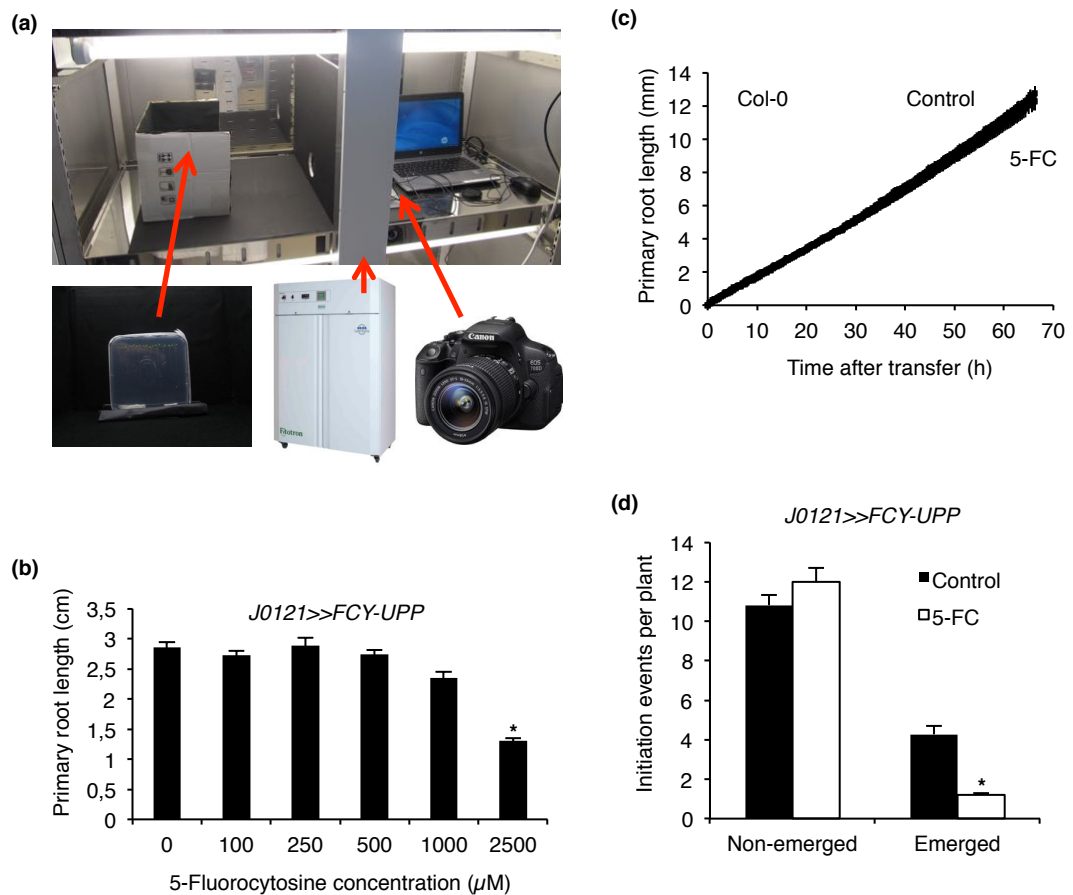


Fig. S2. Real-time root growth tracking setup for real-time tracking and single time point imaging

(a) A reflex camera was used to acquire images every 10 minutes. Setup was achieved in order to reduce light reflection and increase image quality for subsequent analysis by the RootTrace software. (b) Primary root length was measured 6 days after germination for various 5-FC concentrations (0, 100, 250, 500, 1000 and 2500 μM) in the *J0121>>FCY-UPP* seedlings. (c) Real-time primary root growth tracking of non-treated (control) versus 500 μM 5-fluorocytosine treated (5-FC) wild-type (*Col-0*) seedlings for 70 hours after transfer (data represent mean \pm sem, $n=10$). (d) Number of initiation events was counted under a microscope for control vs. 5-FC treated plants in the *J0121>>FCY-UPP* line (data represent mean \pm sem, $n=10$). Asterisks indicate a significant difference with corresponding control experiment by Student's t-test (* $P < 0.001$; $n=10$).

Figure S3

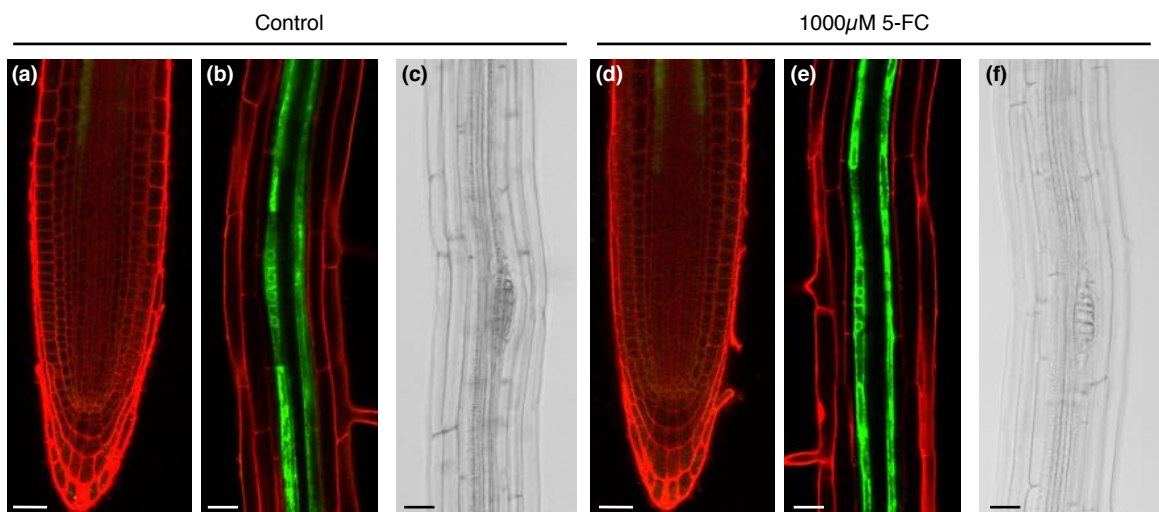


Fig. S3. 5-Fluorocytosine treatment does not alter the expression pattern driven by the J0121 line

(a,b,d,e) The *J0121* line drives expression of *GFP* and *FCY-UPP* in the pericycle cells up to the start of the elongation zone. Treatment with 5-FC blocks lateral root emergence (c vs. f) but does not alter the expression pattern (a,b vs. d,e). Bars are 25 μm.

Figure S4

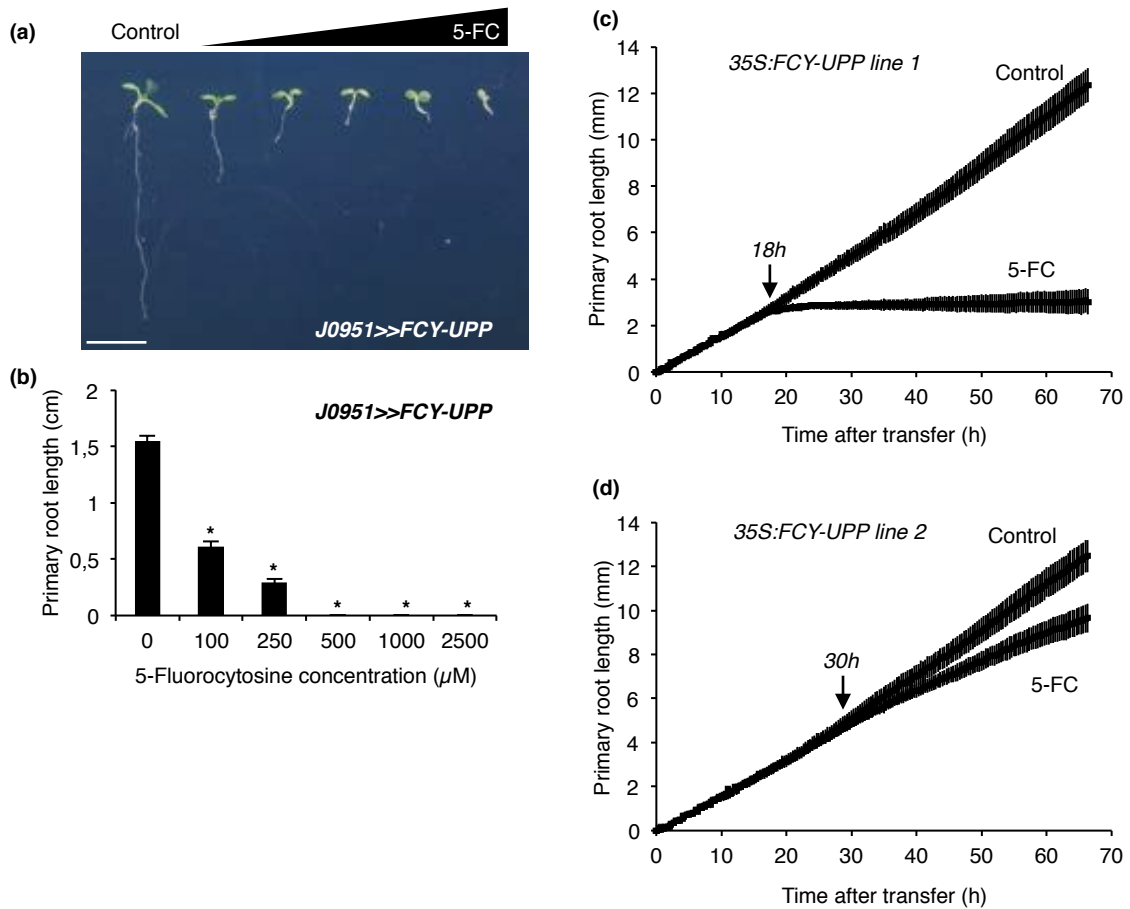


Fig. S4. Lateral root cap and epidermis expression of FCY-UPP blocks primary root growth

(a-b) 6 day-old *J0951>>FCY-UPP* seedlings germinated on various 5-FC concentrations (0, 100, 250, 500, 1000 and 2500 μM). (c-d) Real-time tracking of primary root length in 2 independent *35S:FCY-UPP* lines in non-treated condition (Control) or placed on medium containing 1000 μM 5-FC. Bar is 5mm. Asterisks indicate a significant difference with corresponding control experiment by Student's t-test (* $P < 0.001$; $n = 10$).

Figure S5

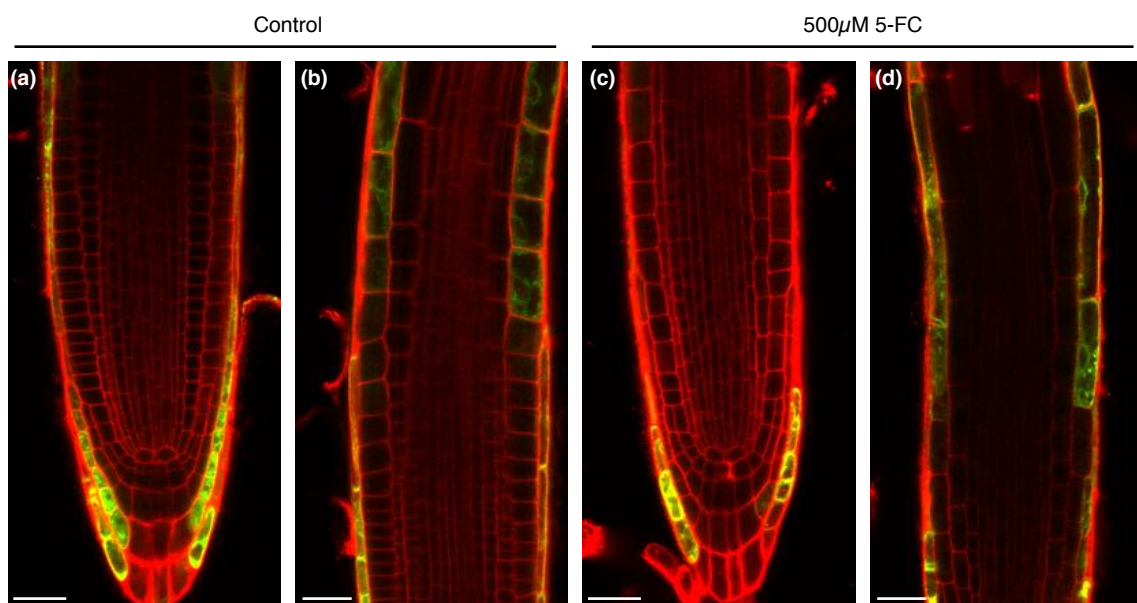


Fig. S5. 5-Fluorocytosine treatment does not alter the expression pattern driven by the J0951 line

(a-d) The *J0951* line drives expression of *GFP* and *FCY-UPP* in the lateral root cap and epidermal cells. Treatment with 5-FC (c,d) blocks primary root growth compared to non-treated plants (a,b) but does not alter the marker line expression pattern. Bars are 25μm.

Figure S6

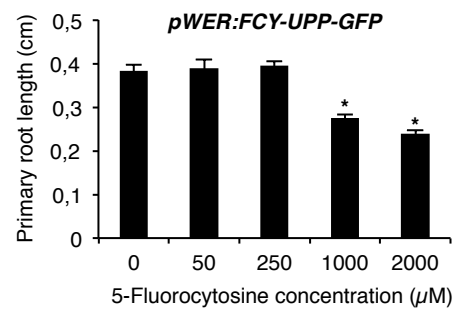


Fig. S6. Dose response of the *pWER:FCY-UPP-GFP* line to 5-Fluorocytosine

Seedlings were germinated on growing concentrations of 5-fluorocytosine (0, 50, 250, 1000 and 2000 μM) and primary root length was measured ($n=20$). Asterisks indicate a significant difference with corresponding control experiment by Student's t-test (* $P<0.001$).

Figure S7

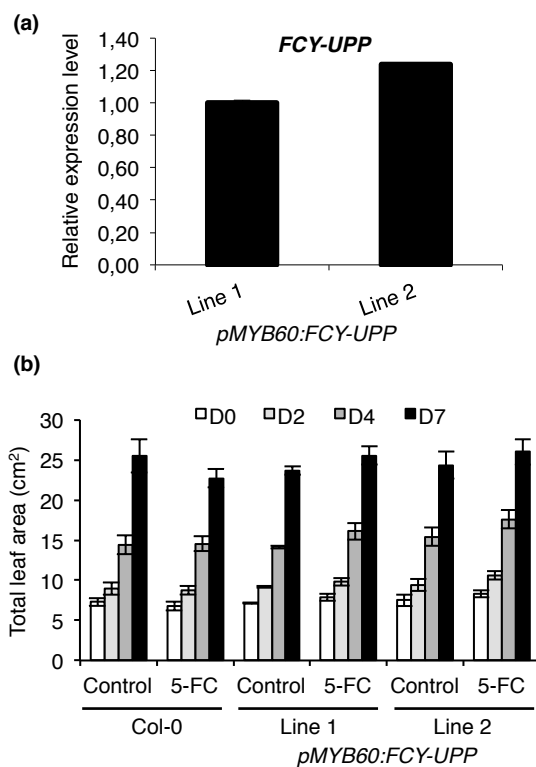


Fig. S7. Expression level of FCY-UPP RNA under the control of the *pMYB60* promoter and leaf area measurement

(a) Relative expression level of the FCY-UPP tandem RNA under the control of the *pMYB60* promoter in 2 independent transgenic lines. (b) Total leaf area was measured in the wild-type (Col-0) and *pMYB60:FCY-UPP* lines in non-treated (Control) and upon 5-FC treatment (5-FC) at day 0 (D0), day 2 (D2) day 4 (D4) and day 7 (D7).