Perspectives for using genetically encoded fluorescent biosensors in plants

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Perspectives for using genetically encoded fluorescent biosensors in plants

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INTRODUCTION

Genetically encoded fluorescent biosensors are increasingly used as the preferred method to visualize and analyse ion fluxes, signalling components, and metabolites, covering an expanding palette of cellular processes. While fluorescent proteins as such are mainly used for localization and expression studies, genetically encoded fluorescent biosensors in addition allow real time studies of cell metabolism with a similar high spatial and temporal resolution. Cell-specific promoters allow biosensor expression in the target cell of choice in contrast to chemical probes that are inherently dependent on efficient delivery into the cells.

The huge interest and progress in the field is reflected in a large number of recent reviews on fluorescent proteins and genetically encoded sensors, e.g., (Fehr et al., 2004; Lalonde et al., 2005; VanEngelenburg and Palmer, 2008; Frommer et al., 2009; Chudakov et al., 2010; Okumoto, 2010; Mehta and Zhang, 2011; Miyawaki, 2011; Newman et al., 2011; Palmer et al., 2011; Okumoto et al., 2012). Several reviews describe plant specific uses, e.g., (Dixit et al., 2006; Frommer et al., 2009; Swanson et al., 2011; Choi et al., 2012; Ehrhardt and Frommer, 2012; Okumoto, 2012; Okumoto et al., 2012). In addition, http://biosensor.dbp.carnegiescience.edu/ provides a database of selected available biosensors.

In the present context, the term genetically encoded fluorescent biosensors refers to fluorescent proteins coupled with a sensing mechanism that causes a change in fluorescence intensity upon ligand binding. Most sensors can be grouped within two major types of fluorescent biosensors: (1) single fluorescent protein sensors, which can carry the sensing mechanism within the fluorescent protein, such as e.g., pHluorins, or where sensing is coupled to a ligand binding domain. Other options using single fluorescent proteins include protein-protein interactions reported by fluorescent protein reconstitution (biFC) or detection of protein translocation. One notable exception of specific plant relevance is the DII-Venus auxin sensor, where degradation of the fluorescent protein is utilized as sensing mechanism. (2) FRET-based sensors, where ligand binding causes a conformational change of the sensor leading to a change in FRET ratio between two fluorescent proteins, usually CFP/YFP variants. Within these groups many sensor platform designs are possible, which are described in detail elsewhere, see e.g., (Okumoto et al., 2012).

There is general consensus that the field is expanding and far from saturated with respect to sensor targets, the quality and variety of the fluorescent proteins, spatiotemporal resolution, compartmentation, and to imaging techniques. This paper discusses the perspectives for using genetically encoded fluorescent biosensors in plants, summarizing the specific challenges plant cell biologists are faced with and the ways they have been overcome so far. Although, due to space restrictions, this review focuses on fluorescent biosensors, the aspects discussed apply to luminescent biosensors as well. What are the expectations for fluorescent biosensors in plants in the future? Can they help in assigning a function to the many orphan receptor-like kinases or create complete flux maps of metabolite and ions in Arabidopsis and other model organisms as suggested by (Okumoto et al., 2012)? We will point to some challenges that need to be addressed, if biosensors are to be used more widely.

WHY ARE GENETICALLY ENCODED FLUORESCENT BIOSENSORS LESS USED IN PLANTS THAN IN MAMMALIAN CELLS?

The variety of genetically encoded fluorescent sensors is explored primarily in mammalian systems. Although these sensors offer highly attractive advantages for plant cell imaging, reports on physiological measurements in plants have been comparatively few, which might indicate that using these tools for live physiological experiments in plants is not trivial.

Table 1 below is a compilation of genetically encoded fluorescent sensors used for physiological experiments in plants. Several important insights into plant cell biology have been gained from...
Table 1 | Genetically encoded fluorescent sensors used for physiological experiments in plants, subdivided by sensor function.

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>FPs</th>
<th>Kd/pKa</th>
<th>Plant species, tissue</th>
<th>Localization</th>
<th>Stimulus/response</th>
<th>References</th>
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<tbody>
<tr>
<td><strong>CAMELEONS AND OTHER CALCIUM SENSORS</strong></td>
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<tr>
<td>YC2.1</td>
<td>ECFP: EYFP</td>
<td>100 nM, 4.3 μM</td>
<td>A. t. guard cells</td>
<td>Cytosol</td>
<td>ABA pathogen elicitors CO2</td>
<td>Allen et al., 1999a,b, 2000, 2001, 2002; Hugouvieux et al., 2001; Klusener et al., 2002; Young et al., 2006; Siegel et al., 2009; Miyawaki et al., 1999</td>
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<td></td>
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<td>(biphasic)</td>
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<td>Watahiki et al., 2004</td>
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<td></td>
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<td></td>
<td>L. longiflorum, N. tabacum, pollen tubes</td>
<td>Cytosol, nucleus</td>
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<tr>
<td>nupYC2.1</td>
<td></td>
<td></td>
<td>M. truncatula root hairs, wt and symbiotic defect mutants</td>
<td>Cytosol, nucleus</td>
<td>Nod factor, mycorrhiza, Mastoparan, JA</td>
<td>Miwa et al., 2006a,b; Sun et al., 2007; Kosuta et al., 2008; Sieberer et al., 2009; Capoen et al., 2011</td>
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<tr>
<td>YC3.1</td>
<td>ECFP: EYFP</td>
<td>1.5 μM</td>
<td>N. tabacum, pollen tube A. t. pollen grain, pollen tubes, papilla cells</td>
<td>Cytosol</td>
<td></td>
<td>Iwano et al., 2004</td>
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<tr>
<td>YC3.6</td>
<td>ECFP-cpVENUS</td>
<td>250 nM</td>
<td>A. t. roots, A. t. N. tabacum, pollen tubes</td>
<td>Cytosol</td>
<td>Glu, ATP, A^{3+}</td>
<td>Haruta et al., 2008; Rincon-Zachary et al., 2010, Nagai et al., 2004</td>
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<td>Iwano et al., 2009</td>
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<td>A. t. guard cells</td>
<td>Cytosol</td>
<td>Methyl Jasmonate (MeJA)</td>
<td>Weinl et al., 2008; Munemasa et al., 2011</td>
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<td>A. t. rosette leaves</td>
<td>Cytosol</td>
<td>Butyrate, ABA, MeJA</td>
<td>Islam et al., 2010</td>
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<td></td>
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<td></td>
<td>A. t. roots, cotyledons</td>
<td>PM, nucleus, cytosol</td>
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<td>Krebs et al., 2012</td>
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<tr>
<td>YC4.6</td>
<td>ECFP: VENUS</td>
<td>58 nM, 14.4 μM</td>
<td>A. t. pollen tubes</td>
<td>ER</td>
<td></td>
<td>Iwano et al., 2009</td>
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<td>Nagai et al., 2004</td>
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<tr>
<th>Sensor name</th>
<th>FPs</th>
<th>Kd/pKa</th>
<th>Plant species, tissue</th>
<th>Localization</th>
<th>Stimulus/response</th>
<th>References</th>
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<tbody>
<tr>
<td>D3cpv-KVK-SKL</td>
<td>ECFP-cpVENUS</td>
<td></td>
<td>A. t. leaves, guard cells</td>
<td>Peroxisomes</td>
<td>Ca^{2+}</td>
<td>Costa et al., 2010; Palmer et al., 2006</td>
</tr>
<tr>
<td>D3cpv</td>
<td>0.6 μM</td>
<td>A. t. Roots, cotyledons</td>
<td>Tonoplast</td>
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<td>Krebs et al., 2012</td>
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<td><strong>pH SENSORS</strong></td>
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<tr>
<td>pHluorin (ratiometric)</td>
<td>GFP</td>
<td>pKa 6.9</td>
<td>N. tabacum, pollen tubes</td>
<td>Cytosol</td>
<td></td>
<td>Certal et al., 2008; Michard et al., 2008; Miesenbock et al., 1998</td>
</tr>
<tr>
<td>PE-pHluorin PR-pHluorin</td>
<td>GFP</td>
<td>pKa 6.6</td>
<td>Ex 395/475 PE:Em 480/512 PR:Em 515</td>
<td>A. t. protoplasts PSB-D, PSB-L</td>
<td>Cytosol, vacuole, mitochondria, chloroplast endomembr. compartments</td>
<td>Shen et al., 2013</td>
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<tr>
<td>Pt-GFP</td>
<td>Pt-GFP</td>
<td>pKa 7.3 (7.8)</td>
<td>475/509 (ex) 508 (em)</td>
<td>A. t. roots, leaves guard cells</td>
<td>Cytosol</td>
<td>Schulte et al., 2006</td>
</tr>
<tr>
<td>GFP H148D</td>
<td>GFP</td>
<td>pKa 7.8</td>
<td>A. t. roots, root hairs</td>
<td>Cytosol</td>
<td>Gravitropism touch, barrier</td>
<td>Fasano et al., 2001; Monshausen et al., 2007, 2009, Esliger et al., 1999</td>
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<tr>
<td>pHusion</td>
<td>mRFP1-EGFP</td>
<td>pKa 5.8 (6.0)</td>
<td>EGFP: 488/507 mRFP1: 584/607</td>
<td>A. t. leaf mesophyll, roots</td>
<td>Cytosol, apoplast</td>
<td>IAA</td>
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<td><strong>REDOX SENSORS</strong></td>
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<tr>
<td>Cyt-RoGFP1</td>
<td>Cyt-GRX1- RoGFP1 c-RoGFP1/2</td>
<td>mRFP1</td>
<td>Mid point potential</td>
<td></td>
<td>A. t. leaf discs, leaf epidermis, plastids, mitochondria</td>
<td>Dark, (age), inhibitor/abiotic, stress</td>
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<td>Dark, (age), inhibitor/abiotic, stress</td>
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<tr>
<th>Sensor name</th>
<th>FPs</th>
<th>Kd/pKa</th>
<th>$\lambda_{\text{max}}^{\text{ex./em.}}$</th>
<th>Plant species, tissue</th>
<th>Localization</th>
<th>Stimulus/response</th>
<th>References</th>
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<tbody>
<tr>
<td>RoGFP1</td>
<td>c-RoGFP1/2Px-RoGFP2</td>
<td>RoGFP2: $\lambda_{\text{max}}$ oxidized: 398 nm reduced: 492 nm</td>
<td>N. tabacum, leaf epidermis, leaf discs</td>
<td>Cytosol, peroxisomes, plastids, ER</td>
<td>Inhibitors/abiotic stress</td>
<td>Schwarzland et al., 2008, 2009</td>
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<td>H$_2$O$_2$: HyPer</td>
<td>cpYFP</td>
<td>Ex. 420/500 Em. 516</td>
<td>N. tabacum leaves, A. t. leaves pre-/post-bolting, guard cells</td>
<td>Cytosol, peroxisomes</td>
<td>Ca$^{2+}$</td>
<td>Costa et al., 2010</td>
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<td>OTHER SENSORS</td>
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<tr>
<td>Chloride: Clomeleon</td>
<td>ECFP-EYFP</td>
<td>ECFP: 434, 477</td>
<td>A. t. roots</td>
<td>Cytosol</td>
<td>Salt stress, Mg$^{2+}$, Ca$^{2+}$, La$^{3+}$, A9C (anion chan. block.)</td>
<td>Lorenzen et al., 2004; Plieth and Saleh, 2013, Kuner and Augustine, 2000</td>
<td></td>
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<tr>
<td>Glucose: FlipGlu600</td>
<td>ECFP-EYFP</td>
<td>600 $\mu$M, 2 mM, 170 nM</td>
<td>A. t. silencing mutants and wildtype, roots, leaves</td>
<td>Cytosol</td>
<td>Glucose flux and levels</td>
<td>Deuschle et al., 2006; Chaudhuri et al., 2008, 2011</td>
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<tr>
<td>Sucrose: FlipSuc90</td>
<td>ECFP-EYFP</td>
<td>88 $\mu$M</td>
<td>A. t. silencing mutants, roots</td>
<td>Cytosol</td>
<td></td>
<td>Chaudhuri et al., 2008</td>
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<tr>
<td>Glutamine: D157N</td>
<td>ECFP-Venus</td>
<td>6 mM (5.15 mM)</td>
<td>A. t. silencing mutants roots</td>
<td>Cytosol</td>
<td></td>
<td>Yang et al., 2010</td>
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<tr>
<td>PtdIns3P,4P, (4,5)P2:</td>
<td>EYFP/mRFP1</td>
<td>EYFP: 514/427 mRFP1: 584/607</td>
<td>Protoplasts (cowpea, BY2). M. truncatula roots, A. t. seedlings</td>
<td>Localization (PM, golgi, cell plate)</td>
<td>PPIs dynamics</td>
<td>Vermeer et al., 2006; Vermeer et al, 2009; van Leeuwen et al., 2007</td>
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<tr>
<td>Auxin: DII-VENUS</td>
<td>Venus</td>
<td>Venus: 515/528</td>
<td>A. t. leaves, roots</td>
<td>Nucleus</td>
<td>Gravitropism</td>
<td>Brunoud et al., 2012</td>
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</table>

Details of the sensors: Dissociation constants, (Kd), pKa-values (of the pH sensors), with in vivo values in brackets, type of FP used, tissue, species, and potentially applied stimulus are given, as well as references to the original plant experiments. A.t. refers to Arabidopsis thaliana. References to Kd/pKa values and spectral properties of the sensors are shown in bold.
their use. Notably, applications of the Ca$^{2+}$-sensing Cameleons have given substantial insight into the role of calcium in stomatal opening (Allen et al., 1999a,b) as well as the role of calcium gradients in growing pollen tubes (Michard et al., 2008), root hairs of Arabidopsis (Monshausen et al., 2007), Nod factor-induced nuclear calcium transients in M. truncatula root hair cells (Capoen et al., 2011) and visualization of Ca$^{2+}$-dynamics in response to auxin during root gravitropism (Monshausen et al., 2011). Also pH sensors have been useful in plants. The pHluorin sensors have been used to document in detail cytosolic pH gradients and oscillations in growing pollen tubes (Michard et al., 2008), and cell wall pH has been measured by use of pHluorins (Gao et al., 2004) or apo-pHusion (Gjetting et al., 2012) secreted to the apoplast.

Looking closer at these experiments, some obvious similarities are seen. It can be argued that successful experiments are often carried out in single cell systems, such as guard cells, root hairs and pollen tubes, where complex cell-to-cell communication is limited. These experiments are all studies of ion signaling, that can be directly correlated with a growth or turgor response, making them attractive experimental setups. Although this is a trend, indeed, several experiments have been successfully carried out in intact tissue, very often in roots, (Fasano et al., 2001; Rincon-Zachary et al., 2010; Monshausen et al., 2011; Gjetting et al., 2012) where autofluorescence is negligible and access is not hindered by the waxy cuticle. Sensors that were successfully used for physiological measurements in intact tissue were often developed specifically for use in plants (e.g., the auxin sensor, DII-Venus, and the apoplastic pH-sensor apo-pHusion). Secondly, it is noted that overall only few sensor platforms and targets were used, again reflecting the fact that many sensors are originally designed for mammalian purposes. Thirdly, sensors were most often expressed in the cytosol, which is the default expression if not specifically targeted to other compartments, and finally most experiments were carried out in Arabidopsis or tobacco, which may not be surprising, since these are easy to manipulate. These observations emphasize some specific challenges that have to be addressed in order to broaden the palette of successful sensor applications in plants.

**PLANT-SPECIFIC FEATURES THAT LIMIT THE APPLICABILITY OF GENETICALLY ENCODED FLUORESCENT SENSORS**

**AUTOFLUORESCENCE FROM CHLOROPLASTS AND CELL WALLS**

Plants are complex, multicellular organisms to work with, and fluorescent probes do not always penetrate multiple cell layers, largely due to the barrier formed by the waxy cuticle and the cell wall. Therefore, genetically encoded sensors are ideally suited for plant cell imaging. However, in plants autofluorescence is a major challenge, particularly in photosynthesizing tissue (chlorophyll ex. 420–460 nm/em. 600–700 nm) and from the cell wall (various components are excited by UV to blue wavelengths, emitting mainly blue light), which can be addressed by the choice of fluorophores in sensor design, or may be circumvented, when lower photon counts/densities can be tolerated, by the use of bioluminescent proteins, such as Aequorin (Mehlmer et al., 2012), where excitation is caused by a chemical reaction instead of light, thus avoiding excitation of autofluorescence.

**PRECAUTIONS FOR MOUNTING PROCEDURES AND STUDYING EXTERNALLY APPLIED CHEMICAL STIMULI**

Genetically encoded sensors as such are non-invasive, but their application to study cellular responses to chemical stimuli requires a perfusion setup and immobilization for microscopy, which can potentially harm the cells. The cuticle covering aerial tissues is an entrance barrier for many compounds, and sometimes even for the ligand itself, making in vivo calibrations difficult when using such sensors. Efficient immobilization methods ensure that no movement of the specimen takes place, while at the same time allowing for perfusion of the chemical stimulus and plant growth. It was, however, recently shown that the commonly used method to immobilize Arabidopsis tissue with a medical adhesive severely impairs cell viability of root cells (Gjetting et al., 2012), making alternative methods necessary. An alternative could be the newly developed root chip (Grossmann et al., 2011) or more simply mounting roots on agarose (Gjetting et al., 2012). Another common method used e.g., for cross-fixing pollen tubes on polylysine slides (Michard et al., 2008) was also shown to disrupt Arabidopsis root cells. In general, the act of handling living tissue under a microscope will inevitably cause disturbance of the tissue and induce various stress responses and tropisms. This of course affects live imaging methods of genetically encoded fluorescent sensors as well as other methods.

**GENE SILENCING MAY BE CAUSED BY CHOICE OF PROMOTER OR TANDEM FLUORESCENT PROTEINS**

Gene silencing has often been mentioned as a particular problem for plant expression of genetically encoded fluorescent biosensors, particularly when used in tandem repeats, or driven by the 35S promoter (Miyawaki et al., 1997; Deuschle et al., 2006; Krebs et al., 2012). This problem was solved in one case by replacing the 35S-promoter of viral origin with the plant-derived UBQ10 promoter in Arabidopsis (Krebs et al., 2012), or by expressing the sensor in transgene silencing mutants (Deuschle et al., 2006). The use of silencing mutants however, is not optimal, since their general growth pattern is changed, and may influence the measurements in unpredictable ways. In our lab, the 35S-promoter did not provoke inhibitory gene silencing when driving the expression of either FRET-based sensors or ratiometric pH sensors (Gjetting et al., 2012 and unpublished results). Transgene silencing in root tips and seedlings was reported to cause a reduction in fluorescence intensity and thus undetectable FRET changes after 10–15 days of growth (Deuschle et al., 2006; Chaudhuri et al., 2011). In contrast, we were able to monitor pH changes in leaves of 1–2 months old plants which were not subject to silencing (Gjetting et al., 2012).

**THE APOPLAST**

This plant-specific extracellular compartment plays a major role in transport regulation, but obviously only plant scientists are interested in developing methods to study its dynamics. Sensors for apoplastic measurements must deal with the low pH values,
which are disruptive to many fluorescent proteins, and also be able to measure large differences in ion or solute concentration in the much less buffered apoplast. Apoplastic pH sensors have been used to measure salt stress (Schulte et al., 2006) and the effect of externally applied auxin (Gjetting et al., 2012), but the targeting of sensor protein to the apoplast results in accumulation in the ER, which should be taken into account when measuring the ratio. However, this accumulated protein could potentially be used as an internal pH reference or even as a tool to study pH in the endomembrane system as well. Another issue with apoplastic measurements relate to the structure of GFP in that an oxidizing environment, such as the cell wall and ER can impair proper folding of the fluorescent protein. The use of superfolder GFP (sfGFP) variants may in time be helpful in plants for solving this problem (Aronson et al., 2011).

**IMPROVEMENT OF SENSOR APPLICATIONS IN PLANTS**

**INCREASING SENSOR TARGET RANGE TO INCLUDE, E.G., HORMONES AND KINASES**

There are many possibilities to expand the range of sensor targets in plants. Developing sensors for central, plant-specific signaling events, like hormone action or activity of plant-specific receptor-like kinases would be major landmarks. An example is a recently developed auxin sensor, which is a fusion of the YFP variant Venus to the Aux/IAA auxin-interaction domain DII (Brunoud et al., 2012), targeted to the nucleus. Using this sensor, auxin distribution was mapped during gravity sensing and lateral shoot formation in Arabidopsis. For mammalian cells, e.g., a variety of GFP-based biosensors exist for kinases, GTPases, phosphatidylinositols (PtdIns) (Kimber et al., 2002; Yoshizaki et al., 2006; Zhang and Allen, 2007). Such sensors (PtdIns) have only recently emerged in the plant community (Munnik and Nielsen, 2011), probably because plants use different signaling components that cannot be targeted by sensors developed for mammalian systems.

**pH MEASUREMENTS IN ACIDIC COMPARTMENTS**

Sensors in plants have so far mainly been expressed in the cytosol, although several other compartments have also been explored (see Table 1). Indeed, targeted sensors are desirable, e.g., to study cell wall pH-dynamics (Gao et al., 2004; Gjetting et al., 2012). Sensor secretion to the apoplast involves accumulation of protein in transit in the endomembrane system, which is a problem to be considered carefully. This may be the reason that some researchers prefer pH-sensitive, small molecular weight fluorescent probes for surface pH measurements in Arabidopsis (Bibikova et al., 1998; Monshausen et al., 2011; Geilfus and Muhling, 2012). However, an apoplastic sensor, stably expressed in cells throughout the tissue, and not just the surface is preferable e.g., in roots to study details of the extracellular pH signature of gravitropic responses and auxin signaling (Swarup et al., 2005). The localization of pH sensors in the acidic compartment of the apoplast or vacuole is also hindered by the sensitivity of GFP to acidity (Tsien, 1998). The pH sensor ptGFP, derived from the Orange Seapen, *Ptilosarcus gurneyi* showed increased acid stability compared with avGFP derived pHluorins. PtGFP fluorescence could be fully restored after exposure to pH 3.5, and partially restored down to pH 2.5 and may therefore be more suitable for acidic measurements. In contrast, pHluorins were completely denatured at pH 3.5 (Schulte et al., 2006). Recently, a pHluorin-derived sensor, based on a solubility-modified GFP (sm-GFP) was targeted to the vacuole, and to other endomembrane compartments and used to determine pH of the different compartments (Shen et al., 2013).

**VARIETY OF FPs AND TECHNOLOGY**

Expanding the variety of sensor fluorescent proteins, e.g., by the development of different FRET donor/acceptors would facilitate the study of several ions/metabolites simultaneously, e.g., the commonly linked signaling cascade of intracellular calcium/apoplastic pH, as well as same ion fluxes in several compartments or complex protein-protein interactions. Multiplexed FRET (Piljic and Schultz, 2008) and fluorescence lifetime imaging (FLIM)-FRET (Grant et al., 2008) are becoming more feasible as the variety of spectral variants increases. In *N. benthamiana* leaves a FRET-FLIM assay was used to detect known protein interactions using a FRET pair of the GFP variant Tsapphire as donor, and mOrange as acceptor (Bayle et al., 2008). A similar approach was used to detect a flavonoid metabolon in Arabidopsis protoplasts (Crosby et al., 2011). These examples are not using genetically encoded sensors as such, and are based on transient expression in single cell systems, but further illustrate the possibilities of using fluorescent protein technology in plants and may be useful for sensor construction at a later stage.

**IDENTIFICATION OF NEW GENES AND GENE FUNCTION**

Genetically encoded sensors may also be used to identify the role of genes of unknown function. A new class of glucose efflux transporters, SWEETs was identified by FRET-based glucose sensors (Chen et al., 2010), and repeated with a sucrose sensor, identifying a subclade of SWEET efflux transporters involved in sucrose transport, indicating a role in phloem loading (Chen et al., 2011). Another promising sensor application known from animal systems, addressed the functional identification of unknown signaling components. This idea was elegantly adapted to Arabidopsis, where the luminescent calcium sensor Aequorin was used to identify an extracellular signaling peptide, AtRALF1, (rapid alkalization factor) by its ability to induce a cytosolic Ca$^{2+}$-increase (Haruta et al., 2008). The effect of this peptide was subsequently analysed in detail in Arabidopsis roots expressing the Cameleon sensor YC3.6.

**CONCLUDING REMARKS**

The use of genetically encoded sensors in plants faces some specific challenges not shared with the mammalian world, which need to be addressed by plant scientists. Nevertheless, the continuous development and refinement of fluorescent proteins, sensor design and bioimaging techniques make genetically encoded sensors very promising tools for elucidating metabolic networks and signaling events in plant cells in the future.
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Genetically encoded fluorescent biosensors in plants


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