SnRK2 Protein Kinases and mRNA Decapping Machinery Control Root Development and Response to Salt

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**SNF1-RELATED PROTEIN KINASES 2 (SnRK2) are important components of early osmotic and salt stress signaling pathways in plants. The Arabidopsis (Arabidopsis thaliana) SnRK2 family comprises the abscisic acid (ABA)–activated protein kinases SnRK2.2, SnRK2.3, SnRK2.6, SnRK2.7, and SnRK2.8, and the ABA-independent subclass 1 protein kinases SnRK2.1, SnRK2.4, SnRK2.5, SnRK2.9, and SnRK2.10. ABA-independent SnRK2s act at the posttranscriptional level via phosphorylation of VARICOSE (VCS), a member of the mRNA decapping complex, that catalyzes the first step of 5’ mRNA decay. Here, we identified VCS and VARICOSE RELATED (VCR) as interactors and phosphorylation targets of SnRK2.5, SnRK2.6, and SnRK2.10. All three protein kinases phosphorylated Ser-645 and Ser-1156 of VCS, whereas SnRK2.6 and SnRK2.10 also phosphorylated VCS Ser-692 and Ser-680 of VCR. We showed that subclass 1 SnRK2s, VCS, and 5’ EXORIBONUCLEASE 4 (XRN4) are involved in regulating root growth under control conditions as well as modulating root system architecture in response to salt stress. Our results suggest interesting patterns of redundancy within subclass 1 SnRK2 protein kinases, with SnRK2.1, SnRK2.5, and SnRK2.9 controlling root growth under nonstress conditions and SnRK2.4 and SnRK2.10 acting mostly in response to salinity. We propose that subclass 1 SnRK2s function in root development under salt stress by affecting the transcript levels of aquaporins, as well as CYP79B2, an enzyme involved in auxin biosynthesis.**

Soil salinity is one of the biggest constraints of modern agriculture, severely affecting crop productivity (Fita et al., 2015). Plant acclimation to saline conditions relies on early activation of signaling cascades, which trigger protective mechanisms. Crucial components of salt and osmotic signaling pathways are protein kinases (Boudsocq and Laurière, 2005). One group of protein kinases recognized as pivotal regulators of responses to osmotic stress is the plant-specific SnRK2 family (SNF1-RELATED PROTEIN KINASE 2). Except for SnRK2.9, all other nine Arabidopsis (Arabidopsis thaliana) SnRK2 protein kinases have been shown to have an increased kinase activity upon treatment with either abscisic acid (ABA), osmotic stress, or salt stress, whereas differential responsiveness was observed for individual SnRK2 protein kinases (Boudsocq et al., 2004). The Arabidopsis SnRK2 protein kinase subfamily comprises three groups: subfamily 1 includes the ABA-independent kinases (SnRK2.1/SRK2G, SnRK2.4/SRK2A, SnRK2.5/SRK2H, SnRK2.9/SRK2J, SnRK2.10/SRK2B), group 2 consists of those involved in drought responses (SnRK2.7/SRK2F and SnRK2.8/SRK2C), and group 3 kinases are strongly activated by ABA (SnRK2.2/SRK2D, SnRK2.3/SRK2I, SnRK2.6/SRK2E/OST1; Kulik et al., 2011). Members of the plant SnRK2 subfamily have also been identified in tobacco (Kelner et al., 2004), rice (Kobayashi et al., 2004), sorghum (Li et al., 2010), maize (Huai et al., 2008), wheat (Zhang et al., 2016), bean (Li and Assmann, 1996), soybean (Monks et al., 2001), and tomato (Yang et al., 2015).

Activity of SnRK2 protein kinases relies on their autophosphorylation; however activation by another
protein kinase acting upstream has been also proposed (Boudsocq et al., 2007; Fujii et al., 2009). Two crucial residues, Ser-171 and Ser-175, have been found to be phosphorylated independently in the ABA-dependent SnRK2.6 protein, whereas activation of ABA-independent SnRK2.10 relies on sequential phosphorylation of Ser-154 followed by phosphorylation of Ser-158 (Vlad et al., 2010). Members of the ABA-dependent subclass 3 have been most extensively studied so far. SnRK2.2, SnRK2.3, and SnRK2.6 are components of the core ABA signaling pathway (Cutler et al., 2010). Several protein phosphatases from the PP2C clade A family have been shown to act as negative regulators of ABA-dependent SnRK2 kinases (Merlot et al., 2001; Ma et al., 2009; Park et al., 2009; Nishimura et al., 2010). In the absence of ABA, PP2Cs dephosphorylate SnRK2 to maintain their inactive state. ABA triggers the interaction of PP2Cs with ABA receptors PYR/PYL/RCAR (PYRABACTIN RESISTANCE 1/PYR1-LIKE/REGULATORY COMPONENT OF ABA RECEPTOR), thus releasing SnRK2 from their inhibited state (Merlot et al., 2001; Ma et al., 2009; Park et al., 2009; Nishimura et al., 2010). Members of subclass 2, SnRK2.7 and SnRK2.8, interacted with PP2Cs in vitro, whereas interactions in planta with one of the PP2Cs, ABI1 (ABSCISIC ACID INSENSITIVE 1), have been recently shown for SnRK2.8 and also the subclass 1 isoform SnRK2.4, but not for SnRK2.10 (Vlad et al., 2010; Umezawa et al., 2013; Krzywińska et al., 2016). SnRK2.4 and SnRK2.10 can be dephosphorylated by members of the phosphophosphate phosphatase family (Krzywińska et al., 2016). Activity of all ten SnRK2 protein kinases is negatively regulated by SCS (SnRK2-INTERACTING CALCIUM SENSOR; Bucholc et al., 2011). SnRK2.4 and SnRK2.10 have been shown to bind to the phospholipid second messenger phosphatidic acid; however, the effect of this interaction on protein kinase activity remains unknown (Testerink et al., 2004; Julkowska et al., 2015).

Several downstream targets have been identified for subclass 2 and 3 SnRK2s. SnRK2.6 phosphorylates the anion channel SLAC1, the potassium channel KAT1, Atrboh NADPH oxidases, and aquaporin PIP2;2, thereby mediating ABA-dependent stomatal closure. The snrk2.6 knock-out mutant is impaired in closing stomata in low humidity conditions and has a wilting phenotype (Mustili et al., 2002; Yoshida et al., 2002; Geiger et al., 2009; Lee et al., 2009; Sato et al., 2009; Sirichandra et al., 2009; Grondin et al., 2015). SnRK2.6, as well as SnRK2.2 and SnRK2.3, can phosphorylate ABA RESPONSIVE ELEMENTS-BINDING FACTORS AREB1, AREB2, and ABF3, bZIP transcription factors that bind to ABA-responsive elements in promoters of ABA-dependent genes (Furihata et al., 2006; Fujii et al., 2007). The snrk2.2/snrk2.3/snrk2.6 triple mutant is insensitive to ABA and has low tolerance to drought, confirming the role of SnRK2 subclass 3 kinases as major regulators of ABA responses (Fujii and Zhu, 2009; Fujita et al., 2009). SnRK2 subclass 3 and/or kinase(s) downstream of this group of SnRK2s can also phosphorylate mitogen-activated protein kinases MPK1, MPK2, and MPK6, another class of ABA-activated protein kinases (Droillard et al., 2002; Umezawa et al., 2013; Wang et al., 2013). A recent phosphoproteomics study identified many putative SnRK2 subclass 3 targets that are involved in DNA and RNA binding and microRNA regulation, but their direct phosphorylation by these kinases still needs to be confirmed (Umezawa et al., 2013, Wang et al., 2013). SnRK2.8 phosphorylated ABF3 (redundantly to SnRK2 subclass 2 proteins) and additionally targeted EEL, another ABF transcription factor (Mizoguchi et al., 2010). Moreover, SnRK2.8 phosphorylated three 14-3-3 proteins, adenosine kinase, glyoxylase I, and ribose 5-phosphate isomerase, which links its function to the regulation of metabolic processes (Shin et al., 2007).

Recently subclass 1 SnRK2 protein kinases have been shown to regulate plant responses to osmotic stress at the posttranscriptional level. SnRK2.1, SnRK2.4, SnRK2.5, SnRK2.9, and SnRK2.10 phosphorylated VCS (VARICOSE), a member of the mRNA decapping complex and crucial component of 5’ mRNA decay pathways (Soma et al., 2017). Also, two dehydrins, ERD10 and ERD14, have been found as a direct phosphorylation targets of SnRK2.10 in responses to salt stress (Maszkowska et al., 2019). Moreover, SnRK2.4 and SnRK2.10 are involved in reactive oxygen species homeostasis upon salt stress, but the mechanism of this regulation remains unknown (Szymańska et al., 2019).

In Arabidopsis roots, SnRK2.4 and SnRK2.10 are activated within 30 s of exposure to salt and both were shown to function as positive regulators of root growth under saline conditions (McLoughlin et al., 2012). snrk2.4 knock-out mutants showed a decreased main (primary) root length in the presence of salt, whereas snrk2.10 knock-out mutants exhibited reduced lateral

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D.K. performed most of the experiments; D.K. and A.M.A. performed RNA-seq analysis; D.K. and C.T. designed and planned research, analyzed the results, and wrote the article with contributions from all authors; A.J.M. provided technical assistance to D.K.; H.L.D. performed MS analysis of in vitro phosphorylation assays; K.G., E.V.D.S., and G.d.J. performed the TAP experiments and MS analysis; J.M., M.B., and G.D. provided protein expression constructs; G.d.J., R.C.S., M.A.H., and C.T. supervised the experimental work and analysis; C.T. conceived the project and obtained funding.

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SnRK2s and Their Targets Shape Root Architecture

In order to identify putative up- and downstream SnRK2 subclass 1 protein kinases targets, we performed in vitro kinase activity assays. We selected VCS, VCR, and DCP2 for verification, because they were previously found to be phosphorylated under salt stress (Stecker et al., 2014). Purified recombinant protein kinases SnRK2.4 and SnRK2.10 were used for the in vitro phosphorylation reactions with synthetic peptides from VCS, VCR, and DCP2 proteins. Synthetic peptides were designed to contain the phosphopeptides identified in the TAP experiment and shown previously to be regulated by osmotic and/or salt stress (Table 2; Stecker et al., 2014; Maszkowska et al., 2019). Each protein kinase was incubated with a mixture consisting of three peptides representing the VCS sequence, and one peptide each from VCR and DCP2. In a separate reaction, MBP (myelin basic protein) was used as a positive control. SnRK2.4 did not phosphorylate itself nor any of the tested peptides; however, it was able to phosphorylate VCS and VCR, and SnRK2.6 phosphorylated all the peptides, whereas SnRK2.5 phosphorylated VCR and two out of three VCS peptides (Table 2).

To investigate whether other members of SnRK2 family can phosphorylate the same peptides as SnRK2.10, SnRK2.5, and SnRK2.6, from subclass 3 were tested. SnRK2.6 phosphorylated all the peptides, whereas SnRK2.5 phosphorylated VCR and two out of three VCS peptides (Table 3; Supplemental Tables S5 and S6).
### Table 1. List of putative SnRK2.4 and SnRK2.10 interactors

Proteins were identified by LC-MS/MS after TAP from Arabidopsis suspension cultures. GSrhino N- and C-terminal fusions with SnRK2.4 and SnRK2.10 were used as baits with two technical replicates. Table presents proteins identified with at least two peptides for each sample.

<table>
<thead>
<tr>
<th>Purified Proteins</th>
<th>GSrhino-SnRK2.4 1</th>
<th>GSrhino-SnRK2.4 2</th>
<th>SnRK2.4-Snrhino 1</th>
<th>SnRK2.4-Snrhino 1 Total</th>
<th>GSrhino-SnRK2.10 1</th>
<th>GSrhino-SnRK2.10 2</th>
<th>SnRK2.10-Snrhino 1</th>
<th>SnRK2.10-Snrhino 1 Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT1G10940 ASK1, SNRK2-4, SNRK2.4, SRK2A</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT1G60940 SNRK2-10, SNRK2.10, SRK2B SNF1-related protein kinase 2.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT3G13300 VCS TransducinWD40 repeat-like superfamily protein</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT3G13290 VCR varicose-related</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>AT5G13570 DCP2, TDT, ATDCP2 decapping 2</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT1G77680 ATRRP44B, RRP44 HOMOLOG B, RRP44B, SOV, SUPPRESSOR OF VARICOSE</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT1G54490 AIN1, EIN5, XRN4, ATXRN4</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>AT4G40010 SNRK2-7, SNRK2.7, SRK2F SNF1-related protein kinase 2.7</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>2</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>AT3G22270 PAT1H1, Topoisomerase II-associated protein</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>+</td>
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<td>AT3G56850 AREB3, DPB3 ABA-responsive element binding protein 3</td>
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<td>+</td>
<td>-</td>
<td>+</td>
<td>2</td>
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<td>AT1G49540 ELF2, AtELF2 elongator protein 2</td>
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<td>-</td>
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<td>+</td>
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<td>-</td>
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<td>0</td>
<td>+</td>
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### Table 2. Phosphorylation sites identified within the sequence of SnRK2.4, SnRK2.10, and their putative interactors

Identified phosphorylated Ser and Tyr (pS, pT) are denoted in bold. For each peptide, the localization in the protein is indicated with its start and end position. Peptide expectation value is the number of times an equal or higher score could be expected to be obtained purely by chance. Site analysis % is the probability that the phosphorylation was assigned correctly to particular residue. Sequences of peptides marked with an asterisk were used for design of the synthetic peptides used for in vitro kinase activity assays. Spectrum number corresponds to spectra presented in Supplemental Figure S1.

<table>
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<tr>
<th>Bait</th>
<th>Spectrum No.</th>
<th>Protein Name</th>
<th>Peptide</th>
<th>Peptide Start</th>
<th>Peptide End</th>
<th>Peptide Ion Score</th>
<th>Peptide Expectation Value</th>
<th>Peptide Sequence</th>
<th>Phosphorylation Site Position in Protein Sequence</th>
<th>Phosphorylation Site Analysis %</th>
<th>Phosphorylation Induced by Salt or Osmotic Stress Shown in</th>
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<tr>
<td>SnRK2.4</td>
<td>1</td>
<td>VCS</td>
<td>86</td>
<td>100</td>
<td>66.21</td>
<td>0.00002</td>
<td>TLSYTPPLNLQpSPR</td>
<td>S98</td>
<td>99.98</td>
<td>–</td>
<td></td>
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<tr>
<td></td>
<td>2</td>
<td>VCS</td>
<td>142</td>
<td>156</td>
<td>49.27</td>
<td>0.001</td>
<td>SFPGCSPGIPRVP+SCK</td>
<td>S154</td>
<td>98.83</td>
<td>–</td>
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<tr>
<td></td>
<td>3</td>
<td>VCS</td>
<td>637</td>
<td>662</td>
<td>109.64</td>
<td>0.00000001</td>
<td>TGLPSQTSQSAYATLPQLpSPR*</td>
<td>S660</td>
<td>100.00</td>
<td>Stecker et al., 2014</td>
<td></td>
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<tr>
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<td>4</td>
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<td>662</td>
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<td>0.0002</td>
<td>pTSGLPSQTSQSAYATLPQLzSPR*</td>
<td>T637+S660</td>
<td>98.84</td>
<td>Stecker et al., 2014</td>
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<td>662</td>
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<td>0.004</td>
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<td>Y651+S660</td>
<td>98.77</td>
<td>Stecker et al., 2014</td>
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<td>0.00000001</td>
<td>TSGLPSQTSGAGSAYATLPQLpSPR*</td>
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<td>86.13</td>
<td>Stecker et al., 2014</td>
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<td>835</td>
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<td>VFCQSQNSpSSTEMAR*</td>
<td>S827</td>
<td>99.86</td>
<td>–</td>
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<td>0.0000001</td>
<td>VFCQSQpSNLSTEMAR*</td>
<td>S1153 or S1156</td>
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<td>Stecker et al., 2014; Maszkowska et al., 2019</td>
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<td></td>
<td>9</td>
<td>VCS</td>
<td>1149</td>
<td>1163</td>
<td>60.41</td>
<td>0.0001</td>
<td>VFCQSQpSNLSTEMAR*</td>
<td>S1193 or T1190</td>
<td>64.22/52.49</td>
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<td>1171</td>
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<td>41.43</td>
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<td>NLLAAAGANSGGSNSVpTEpSGpGLpGALLEK</td>
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<tr>
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<td>687</td>
<td>60.03</td>
<td>0.0004</td>
<td>TSpSADFYVR*</td>
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<td>95.12</td>
<td>–</td>
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<td>12</td>
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<td>SKDNVTpDDDVSQSQGpS6AFFEK</td>
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<td>LADATpAGNSLpVpLSGpQLpGALLEK</td>
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<td>Maszkowska et al., 2019</td>
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<td>0.0001</td>
<td>pSpTVpGTPpVpAPVpLSR</td>
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<td>Stecker et al., 2014</td>
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<td></td>
<td>18</td>
<td>VCS</td>
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<td>361</td>
<td>49.63</td>
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<td>TVKEpHApGpVVp</td>
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<td>99.88</td>
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<td></td>
<td>19</td>
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and S6). Because the peptide corresponding to the DCP2 protein was hardly detectable, probably due to its low solubility, full-length DCP2 recombinant protein was purified and tested in an in vitro kinase assay. Also, full-length DCP2 was not phosphorylated in the presence of SnRK2.10, confirming it is not a direct substrate of this kinase in vitro (Supplemental Table S7). We conclude that VCS and VCR are direct targets of SnRK2.5, SnRK2.6, and SnRK2.10 and hypothesize that these protein kinases might be partially redundant.

Components of SnRK2 Subclass 1-Regulated 5′ mRNA Decay Pathway Contribute to Root Development and Root System Architecture Responses to Salt Stress

SnRK2.4 and SnRK2.10 were shown previously to have a positive role in elongation of the main root and in lateral root emergence under salt stress, respectively (McLoughlin et al., 2012). Here, we tested the root system architecture of a quintuple knock-out mutant snrk2.1/2.4/2.5/2.9/2.10 impaired in all SnRK2 subclass I protein kinases (Fujii et al., 2011). Salt-induced changes in root growth were tested by transferring 4-d-old seedlings germinated on half-strength Murashige-Skoog medium to media supplemented with 0, 75, and 125 mM NaCl. At 6 d after transfer, we observed genotype-dependent changes in main root length (MRL). The quintuple mutant snrk2.1/2.4/2.5/2.9/2.10 displayed shorter MRL than ecotype Columbia-0 (Col-0) on all conditions tested. (Fig. 1A; Supplemental Fig. S3, A and D; Supplemental Dataset S1). Due to these differences in the MRL, lateral root growth was assessed by quantification of lateral root density (LRD) and aLRLperMRL (average lateral root length per main root length). Although no differences were observed regarding LRD at any condition tested, the response of aLRLperMRL to salinity differed between Col-0 and the snrk2.1/2.4/2.5/2.9/2.10 mutant, as indicated by two-way ANOVA testing the genotype by salt interaction (Supplemental Fig. S3D). The snrk2.1/2.4/2.5/2.9/2.10 mutant showed a higher aLRLperMRL on 125 mM NaCl (Fig. 1A; Supplemental Fig. S3, A and D; Supplemental Dataset S1). Altogether this suggests that SnRK2 subclass 1 protein kinases promote main root growth regardless of the conditions, whereas under high salinity they inhibit lateral root elongation.

Identification of VCS as a direct substrate of SnRK2 subclass 1 protein kinases, and the emerging role of mRNA metabolism factors in osmotic and salt stress responses, suggests that VCS, similarly to subclass 1 SnRK2s, might be involved in stress-regulated modulations of root system architecture (Kawa and Testerink, 2017; Soma et al., 2017). Therefore, we tested two artificial micro RNA (amiRNA) lines targeting VCS (VCS2 and VCS4; Soma et al., 2017) and two loss-of-function mutants in XRN4 (xrn4-5 and xrn4-6; Souret et al., 2004; Gy et al., 2007) in the same experimental set up as for snrk2.1/2.4/2.5/2.9/2.10. For both VCS amiRNA lines, their response to salt stress in main root and lateral root growth differed from Col-0 (Fig. 1B; Supplemental Fig. 3S, B–D; Supplemental Dataset S2). Although changes in MRL varied in two amiRNA VCS lines tested, which could be attributed to the differences in the level of VCS expression in these lines, VCS had little effect on main root growth (Supplemental Fig. S4A). Both lines showed increased aLRLperMRL under control conditions, whereas under salt stress no differences were detected (Fig. 1C).

The observed decreased MRL, LRD, and aLRLperMRL of the xrn4-6 mutant under all conditions tested was dependent on genotype as well as on the interaction between genotype and the salt stress treatment. The xrn4-5 mutant had a shorter main root, whereas its decrease in LRD and aLRLpMRL in the presence of salt was dependent on the genotype-salinity interaction (Fig. 1C; Supplemental Fig. S3, C and D; Supplemental Dataset S3). Using reverse transcription quantitative PCR (RT-qPCR), we tested the expression of a possible XRN4 mRNA fragment, using primers located upstream of the transfer DNA insertion in both lines. No expression was detected for xrn4-6, confirming it is a true knock-out, whereas the same product was expressed two times higher in the xrn4-5 line than in Col-0 (Supplemental Fig. S4B). Both lines were previously shown to be loss-of-function mutants, producing truncated XRN4 proteins. Because the transfer DNA insertion in xrn4-5 is downstream of the one in xrn4-6, we cannot exclude the possibility that there is some remaining XRN4 activity in xrn4-5, which could explain the weaker phenotype of that line. We conclude that XRN4 has a positive role in lateral root formation and elongation under control and saline conditions.

Together, these results suggest that SnRK2 subclass 1 protein kinases, VCS, and XRN4 contribute to root growth under nonstress conditions as well as in remodeling root system architecture upon salt stress.

Impact of SnRK2 Subclass 1 Protein Kinases on the Salt-Induced Transcriptome in Arabidopsis Seedlings

To further investigate a functional link between SnRK2 subclass 1 protein kinases, mRNA decay pathways and salt stress, transcriptome profiling of Col-0, snrk2.4, double snrk2.4/2.10 (McLoughlin et al., 2012), and quintuple snrk2.1/2.4/2.5/2.9/2.10 (Fujii et al., 2011) knock-out mutants was performed. To select the most suitable duration of salt stress, a time-course experiment with Col-0 seedlings was performed. Seedlings (10 d old) grown in liquid half-strength MS media were treated with buffer (mock) or 150 mM NaCl. Kinase activity in the crude extract of proteins from whole seedlings was assayed by in-gel kinase assay using MBP as a substrate. Salt treatment resulted in rapid induction of SnRK2.4 and SnRK2.10 activity (37 kD band) within 30 s, which was reduced after 5 min and increased again after 24 h (Supplemental Fig. S5), similar to dynamics observed before for roots grown in...
Table 3. SnRK2.5, SnRK2.6, and SnRK2.10 phosphorylate VCS peptides

Summary of the in vitro kinase activity assays performed with recombinant protein kinases and synthetic peptides. Position of start and end of the peptides used is relative to the first amino acid in the protein sequence. MBP is a known substrate for SnRK2 protein kinases and was used as a positive control. –, denotes no phosphorylation detected; NA, not applicable.

<table>
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<th>Substrate</th>
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<th>Protein Kinase</th>
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<td>VCS</td>
<td>MBP</td>
<td>636-668</td>
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hydroponics (McLoughlin et al., 2012). The changes in mRNA levels that we are interested in are likely the consequence of the action of the potential substrates of SnRK2 and may not be observed immediately after SnRK2 activation. Hence, a 1-h salt treatment was chosen for transcriptome profiling (measuring steady state transcript levels by RNA sequencing (RNA-seq) of Col-0, snrk2.4, double snrk2.4/2.10, and quintuple snrk2.1/2.4/2.5/2.9/2.10 mutants.

Because multiple members of the SnRK2 family in rice, wheat, and maize have been shown to be transcriptionally up-regulated by salt and osmotic stress (Kobayashi et al., 2004; Huai et al., 2008; Mao et al., 2010; Zhang et al., 2010, 2011), we checked whether the mRNA abundance of Arabidopsis SnRK2 is regulated by salt stress. The 1-h treatment with 150 mM NaCl resulted in a small up-regulation of only SnRK2.5, suggesting that under these conditions most of the Arabidopsis SnRK2 protein kinases are only regulated at the posttranscriptional level; yet we cannot exclude the possibility that they may be transcriptionally regulated at other time points (Supplemental Fig. S6).

We first investigated the effect of the mutations in genes encoding subclass 1 SnRK2 protein kinases under nonstress conditions (Supplemental Fig. S7A). We identified 44, 68, and 485 genes differentially expressed in snrk2.4, snrk2.4/2.10, and snrk2.1/2.4/2.5/2.9/2.10, respectively, as compared with Col-0 (Supplemental Table S8; Supplemental Fig. S8, A and C). Biological processes and molecular functions enriched among genes with altered expression in snrk2.1/2.4/2.5/2.9/2.10 indicate that subclass 1 SnRK2 protein kinases participate in responses to biotic and abiotic stress as well as secondary metabolite processes (Supplemental Fig. S8B). This suggests that subclass 1 SnRK2s are partially activated under control conditions used here, or have a function in their nonactive state.

Next, we investigated the effect of salt stress in Col-0. Differential gene expression analysis revealed that 1-h treatment of Col-0 seedlings with 150 mM NaCl resulted in a change in expression of more than two times in 1292 genes, among which 913 were up- and 379 were down-regulated (Supplemental Table S9). To assess the consequences of the mutations in SnRK2 subclass 1 protein kinases for the salt responses, for each snrk mutant tested, we checked which genes regulated by salt in Col-0 either (1) remain unaffected in mutant or (2) are affected to a different degree (the ratio of the fold change in response to salt stress is two times higher or lower in the mutant as compared with Col-0; genes up-regulated by salt in Col-0 are down-regulated in the mutant; genes down-regulated by salt in Col-0 are up-regulated in the mutant). To assess the impact of SnRK2 subclass 1 protein kinases specifically on the salt-induced transcriptome, genes for which expression was already altered in the mutant lines in control conditions were subtracted (Supplemental Fig. S7B).

Out of 1292 genes regulated by salt, abundance of 356, 426, and 434 was affected in snrk2.4, snrk2.4/2.10, and snrk2.1/2.4/2.5/2.9/2.10, respectively (Fig. 2, A and C; Supplemental Tables S10–S15). Salt response of 160 genes was altered in single, double, and quintuple mutants (Fig. 2C; Supplemental Table S16). Together, 684 genes were found in at least one mutant tested, suggesting that around 50% of the regulation observed in Col-0 depends on at least some of the subclass 1 SnRK2, whereas the other 50% implies existence of other regulatory pathways acting in parallel to them or a more complex mechanism (Fig. 2, A and C).

Among GO (gene ontology) categories enriched within salt stress–regulated genes with altered abundance in mutants tested, we found biotic and abiotic stress responses shared by all three mutants (Fig. 2B). Interestingly, kinase activity was enriched among genes affected by the snrk2.4 mutation, suggesting that SnRK2.4 alone can regulate, directly or indirectly, expression of other kinases; yet this was not the case for the higher order subclass 1 SnRK2s mutants (Fig. 2B). Several categories (responses to stress, secondary metabolic process, cell death) were enriched among both salt stress–regulated genes and genes with altered mRNA abundance in snrk2.1/2.4/2.5/2.9/2.10 under control conditions.
Expression of several osmotic stress-induced genes previously described to be dependent on SnRK2.2, SnRK2.3, and SnRK2.6 (RD29A, RD29B, RD26, NCED3, PKS5, KIN2, AREB1, HAI1, COR15A, DREB2A, ABI1; Yoshida et al., 2002; Fujita et al., 2009; Fujii et al., 2011) was not affected by any of the mutations tested here, indicating a separation of the effect of subclass 1 and 3 SnRK2 kinases in the regulation of, at least, these genes (Supplemental Tables S10–S15).

Figure 1. Components of SnRK2 subclass 1-regulated 5′ mRNA decay pathways contribute to root development and root system architecture responses to salt stress. Root system architecture of quintuple snrk2.1/2.4/2.5/2.7/2.9/2.10, amiRNA lines VCS#2 and VCS#4, xrn4-5, and xrn4-6. Seedlings (10 d old) were transferred to 0 and 125 mM NaCl at the 4-d-old stage. Main root length, average lateral root length per main root length, and lateral root density of Col-0, snrk2.1/2.4/2.5/2.7/2.9/2.10 (A), amiRNA lines VCS2 and VCS4 (B), xrn4-5 and xrn4-6 (C) on media supplemented with 0 or 125 mM NaCl are shown. Boxplots denote span from 25th to the 75th percentile and are centered to the data median. Asterisk denotes p-value of pairwise comparison by least square method: ***<0.001, **<0.01, *<0.05, n > 30.

Acting downstream of one or more subclass 1 SnRK2s in responses to salinity, 246 were covered in a microarray study by Narsai et al. (2007) and mRNA half-life of 127 of them was shorter than 3 h (Supplemental Table S17), suggesting that these transcripts have low stability. Moreover, 457 of the 684 identified here as SnRK2-dependent candidate genes were recently identified as potential targets of VCS (Sorenson et al., 2018; Supplemental Table S18;) and 29 genes had altered response to dehydration in VCS amiRNA lines (Soma et al., 2017; Supplemental Table S19). Additionally, salinity-dependent regulation of 92 of our candidates was found to be perturbed in the lsn1 (the Sm-like protein 1) mutant (Supplemental Table S20), a member of the decapping activator complex (Perea-Resa et al., 2016).
In order to select genes for further validation, we focused on those with salt stress–regulated expression altered in single, double, and quintuple mutants tested. Although subclass 1 SnRK2 kinases are implicated in multiple biological processes, because of the previously found roles of SnRK2.4/2.10 in modulation of root architecture in salt (McLoughlin et al., 2012), we selected transcripts involved in root development. Out of 160 genes, we found 94 genes with a previously reported role in root development, out of which 91 were associated specifically with lateral root development (Fig. 2C; Supplemental Table S16; Péret et al., 2012; Voß et al., 2015) and 73 of these are potential substrates of VCS (Fig. 2C; Supplemental Table S16).

Figure 2. SnRK2 subclass 1 protein kinases control various biological processes. A, Salt stress regulated expression profiles in Col-0 and snrk2.4, snrk2.4/2.10, and snrk2.1/2.4/2.5/2.7/2.9/2.10. Heatmap presents log2 fold changes (log2FC) in expression of the genes significantly affected by 1-h 150 mM NaCl treatment in Col-0 and corresponding log2FC value in mutants tested. Gray color indicates genes for which expression was not significantly changed (absolute value of log2FC < 1). B, GO categories enriched among the salt stress–regulated genes with altered expression in tested mutants. Heatmap presents corrected p-value (q-value) of the enrichment. Categories that were not enriched in individual genotypes are represented by gray squares (NA). C, Number of salt stress–regulated genes with expression altered in the tested mutants (left). Number of genes acting downstream of subclass 1 SnRK2 protein kinases that are substrates of VCS and have been reported to participate in root development (right) are shown. A detailed list of the genes is presented in Supplemental Table S16.

SnRK2 Subclass 1 Protein Kinases Regulate the Expression of Aquaporins, β-Glucosidase, and a Cytochrome P450

Out of 73 genes that act downstream of subclass 1 SnRK2 protein kinases, are probable targets of VCS, and have a potential role in the root development, we selected four for further characterization. Expression patterns of the four selected candidates were verified by RT-qPCR using RNA extracted from an independent biological experiment. Expression of selected genes was up-regulated by salt stress in Col-0, whereas this induction was not observed in at least one snrk2 mutant, suggesting different levels of redundancy between individual SnRK2 subclass 1 protein kinases (Fig. 3A; Figure 2).
Salt stress–dependent induction of the expression of the aquaporin PLASMA MEMBRANE INTRINSIC PROTEIN 2;5 (PIP2;5) was dependent solely on SnRK2 subclass 1 protein kinases signaling. Expression of PIP2;5 was dependent on SnRK2 subclass 1 protein kinases signaling. Expression of PIP2;5 (A), PIP2;3 (B), BGLU6 (C), CYP79B2 (D), as a ratio of the expression under salt stress salt and control (left), under control conditions (middle), and upon salt treatment (right) in Col-0, snrk2.4, snrk2.4/2.10, snrk2.1/2.4/2.5/2.9/2.10, and xrn4-5 lines is shown. Values present are averages of normalized expression levels of three biological replicates, and error bars denote se. Statistical comparison was done by one-way ANOVA followed by LSD post hoc test ($P < 0.05$). Different letters indicate significant differences.

DISCUSSION

SnRK2.4 and SnRK2.10 protein kinases are involved in early responses to osmotic stress and salinity. Their
rapid activation within the first minutes after salt treatment is independent of ABA, and SnRK2.4 and SnRK2.10 have been shown to promote root growth in the presence of salt (McLoughlin et al., 2012). To understand the ABA-independent mechanism of early salt stress signaling leading to regulation of root growth, we aimed to identify components of SnRK2.4 and SnRK2.10 protein kinase pathways.

In planta copuriﬁcation experiments showed that both kinases can physically interact with several proteins involved in 5’ mRNA decay, among which VCS and VCR were phosphorylated (Tables 1 and 2; Supplemental Table S1). Degradation of mRNA from its 5’ end requires removal of the 5’ cap by the decapping complex followed by the digestion by 5’–3’ exoribonuclease XRN4. Two of the proteins interacting with SnRK2.4 and SnRK2.10, VCS and DCP2, are members of the mRNA decapping complex (Xu et al., 2006). VCS physically interacts with DCP2 as well as DCP1, which is required for the activation of DCP2 decapping activity and assembly of a functional decapping complex (Xu et al., 2006; Goeres et al., 2007). Removal of 5’ cap structure leaves the mRNA unprotected from the exoribonucleic activity of XRN4 (Kastenmayer and Green, 2000). VCS and VCR were the most abundant interactors of SnRK2.4 and SnRK2.10, implying very stable interactions (Tables 1 and 2; Supplemental Table S1). This suggests that, besides being substrates of SnRK2.4 and SnRK2.10, VCS and VCR could be a part of a larger complex involving other proteins (Table 1). We hypothesize that other copurified proteins are not substrates for SnRK2.4 and SnRK2.10, but rather indirect interactors, that might stabilize the VCS-SnRK2.4/2.10 complex; however, this still requires conﬁrmation. Similar copurification experiments reported by Soma et al. (2017) also identiﬁed VCS, VCR, and DCP2 as SnRK2.1 interactors and VCS as a phosphorylation target of all subclass 1 SnRK2 protein kinases. Moreover, it is unlikely that VCS is the only phosphorylation target of subclass 1 SnRK2 protein kinase, and other substrates are yet to be discovered.

Here we mapped the phosphorylation sites in VCS proteins that are targeted by subclass 1 SnRK2 protein kinases (Table 3). Direct phosphorylation of Ser-645, Ser-692, and Ser-1156 of VCS and Ser-680 of VCR by SnRK2.10 was conﬁrmed in in vitro kinase activity assays (Table 3). Another kinase from the SnRK2 subclass 1 subfamily, SnRK2.5, was also able to phosphorylate Ser-645 and Ser-1156 of the VCS peptides, but not VCR, which could possibly be because its lower activity compared with SnRK2.10 (Table 3; Supplemental Table S5). A previous phosphoproteomic study identiﬁed VCS as a putative substrate also for ABA-dependent SnRK2 kinases, and VCS was weakly phosphorylated by SnRK2.2 protein kinase upon osmotic stress (Umezawa et al., 2013, Soma et al., 2017). In our in vitro assay SnRK2.6 was able to phosphorylate VCS and VCR at the same residues as SnRK2.10 (Table 3). Phosphorylation of Ser-645, Ser-692, and Ser-1156 of VCS and Ser-680 of VCR has been previously shown to be up-regulated by osmotic and/or salt stress in planta (Stecker et al., 2014; Maszkowska et al., 2019).

Figure 4. Mode of action of salt stress–induced modulations of root system architecture (RSA) governed by SnRK2 protein kinases. SnRK2 protein kinases are autophosphorylated upon salt stress. Both ABA-independent (in yellow) and ABA-dependent (in pink) SnRK2 protein kinases can phosphorylate VCS. Additional phosphorylation targets were already identiﬁed for SnRK2.6, and for ABA-independent SnRK2s, other phosphorylation substrates remain unknown.Phosphorylation of VCS may affect proper functioning of the decapping complex and lead to either inhibition or enhancement of 5’ mRNA decay. The abundance of PIP2;3, PIP2;5, and CYP79B2 transcripts, among others, depends on the subclass 1 SnRK2s, yet it remains unknown whether it is a consequence of the phosphorylation any of the kinase targets and whether it is direct or indirect regulation. PIP2;3 and PIP2;5 regulate formation and elongation of lateral roots (LR) via control of water ﬂuxes in lateral root primordia (LRP) and CYP79B2 via local auxin biosynthesis. XRN4 activity controls abundance of PIP2;3, PIP2;5, and CYP79B2 via an unknown mechanism. Transcripts for which abundance is affected by salt stress and that modulate main root (MR) elongation remain unknown. Drawings of proteins and processes were reproduced from the model published in Kawa and Testerink (2017). Dashed lines indicate proposed processes that have not been experimentally validated.
Thus, our data now identify both ABA-dependent and independent SnRK2 protein kinases as protein kinases targeting the VCS and VCR phosphosites phosphorylated in vivo. Moreover, two out of three VCS phosphorylation sites, Ser 645 and Ser-690, are located in the intermediate VCS sequence (VCSm) region shown to be phosphorylated by SnRK2.1 SnRK2.4, SnRK2.5, and SnRK2.10 in vitro as well as in plants subjected to osmotic or salt stress (Soma et al., 2017). To date, the consequences of VCS phosphorylation remain unknown, but it is possible that this posttranslational modification can affect assembly of the decapping complex or activity of DECAPPING 2. Since the removal of the 5’ cap exposes an mRNA molecule to the exoribonucleic activity of XRN4, we hypothesize that SnRK2 protein kinases, via phosphorylation of VCS, control 5’ mRNA decay by either enhancing or inhibiting its action. The VCS phosphorylation sites targeted by subclass 1 SnRK2 protein kinases identified here can help to understand the mechanism of this regulation.

Subclass 1 SnRK2s and components of their signaling pathway, identified here as their phosphorylation substrates or proteins acting further downstream, play a role in root development and root responses to salt. At least one of the SnRK2.1, SnRK2.5, or SnRK2.9 isoforms promotes main root growth regardless of NaCl concentration (Fig. 1A; Supplemental Fig. S3, A–D). Activity of SnRK2.4 and SnRK2.10 under salt stress appeared higher than other members of subclass 1 (Supplemental Fig. S5), suggesting higher relevance of SnRK2.4 and SnRK2.10 signaling in response to salt stress over the other class 1 members. At the same time, expression of several salt stress–regulated transcripts was impaired in snrk2.1/2.4/2.5/2.9/2.10, but not in single and double mutants, implying that SnRK2.1, SnRK2.5, and SnRK2.9 signaling can also govern salt-induced changes in gene expression (Fig. 2, Supplemental Tables S10–S15). The decreased main root growth observed here in the quintuple snrk2.1/2.4/2.5/2.9/2.10 mutant regardless of NaCl concentration was also reported for the quadruple snrk2.1/2.4/2.5/2.10 mutant (Soma et al., 2017) and single snrk2.4 mutant (McLoughlin et al., 2012) exposed to salt stress. The quintuple snrk2.1/2.4/2.5/2.9/2.10 mutant had also longer lateral roots under high salinity conditions, suggesting that some of the SnRK2 subclass 1 protein kinases inhibit lateral root growth in response to salt stress (Fig. 1A), whereas interestingly, SnRK2.10 has been shown previously to be a positive regulator of lateral root formation under salt stress (McLoughlin et al., 2012). This suggests that redundancy among subclass 1 SnRK2 protein kinases depends on the environmental conditions and differs between main root and lateral roots.

Among downstream components of the subclass 1 SnRK2s-dependent pathway, VCS inhibited lateral root elongation under nonstress conditions, but this effect was absent under salt stress (Fig. 1B; Supplemental Fig. S3B), which may suggest that the functioning of the decapping machinery is modulated by the environment. The VCS amiRNA lines tested here were previously reported to be more affected in main root length than wild type after 15 d of exposure to salinity (Soma et al., 2017). Here, during a shorter duration of salt stress (6 d), we only observed mild alterations in the main root growth (Fig. 1B; Supplemental Fig. S3B). XRN4 promoted main root and lateral root growth under control and salt stress conditions (Fig. 1C; Supplemental Fig. S3C). Because the xrn4-5 mutant was previously shown to be hypersensitive to ABA at early vegetative stages, it is plausible that observed phenotypes are a consequence of altered ABA sensitivity (Waiver et al., 2018).

Alteration in responses to salt stress in the transcriptome of snrk2.4, snrk2.4/2.10, and snrk2.1/2.4/2.5/2.9/2.10 mutants included genes involved in many biological processes (Fig. 2B; Supplemental Tables S10–S15). Out of 160 genes affected in their responses to salinity in the single, double, and quintuple mutants tested, 110 are potential VCS substrates (Fig. 2C; Supplemental Tables S16 and S18). Expression of only 29 genes had an altered response to 5 h dehydration in VCS amiRNA lines (Supplemental Table S19; Soma et al., 2017), indicating that VCS might target different genes under osmotic and salt stress and this process depends on the duration of stress exposure. Although transcripts previously reported to be controlled by SnRK2-regulated mRNA decapping had enhanced mRNA decay rates (Soma et al., 2017), here we also identified transcripts up-regulated by salt and show that this pathway might also operate via stabilization of another set of mRNAs (Fig. 3). It is still not clear whether the regulation of the mRNA abundance of PIP2;3, PIP2;5, BGLU6, and CYP79B2 are consequences of the phosphorylation of VCS or other potential substrates on subclass 1 SnRK2s (Fig. 4). Some changes in transcript abundance in response to salt observed in snrk mutants may be also linked to the activity of XRN4, yet the mechanism of this control remains unclear (Fig. 3; Supplemental Fig. S9). If these transcripts would be direct targets of XRN4 5’ exoribonuclease activity, one would expect higher levels, rather than the observed lower levels in the xrn4-5 mutant compared with Col-0, suggesting that the observed changes are a consequence of the 5’ decay of transcripts acting upstream of PIP2;5, CYP79B2, and BGLU6. It is also plausible that in the absence of XRN4, the exosome becomes the dominant decay machinery (Zhang et al., 2015), but in that case, targeted transcript levels in xrn4-5 mutant would resemble ones in Col-0.

Out of 110 genes affected in their responses to salinity in the single, double, and quintuple mutants tested and previously described as potential VCS substrates, 73 have a role in root development (Fig. 2C; Supplemental Table S16 and S18). Aquaporins have already been shown to facilitate water transfer to the LR primordium from its overlying tissues and thereby controlling LR emergence, suggesting that the roles of PIP2;5, PIP2;3, and SnRK2.10 overlap (Peret et al., 2012). Overexpression of PIP2;5 in barley resulted in increased root
growth under saline conditions (Alavilli et al., 2016). Interestingly, yet another aquaporin, Pip2;1, was phosphorylated by SnRK2.6 (Grondin et al., 2015), suggesting that function of aquaporins can be regulated by SnRK2 kinases via two mechanisms: ABA-dependent via direct phosphorylation and indirectly at the transcript level by non-ABA dependent SnRK2s. Recently the cytochrome P450 protein CYP79B2 was shown to regulate lateral root formation and elongation under salt stress (Julkowska et al., 2017), and natural variation in salinity induced expression of CYP79B2 positively correlated with lateral root development under salt stress (Julkowska et al., 2017). Remarkably, CYP79B2 is expressed at the sites of lateral root formation, a similar localization of which was found for SnRK2.10 (Ljung et al., 2005; McLoughlin et al., 2012). CYP79B2, via the conversion of Trp to indole-3-acetaldoxime, is involved in local biosynthesis of auxin, the key hormone regulating root development (Mikkelsen et al., 2000; Ljung et al., 2005). This, together with the fact that the expression of Pip2;2 and Pip2;5 are regulated by auxin (Péret et al., 2012), suggests that subclass 1 SnRK2s may modulate root development in response to salinity via auxin-related processes. SnRK2.10 were also required for salinity-dependent induction of the flavonol glucosyltransferase BGLU6 (Fig. 3C), which by regulation of flavonol metabolism can contribute to scavenging reactive oxygen species accumulating upon salt stress (Agati et al., 2012; Ishihara et al., 2016).

To summarize, our results suggest that both subclass 1 SnRK2 protein kinases and the 5’ mRNA decay machinery can regulate root growth in the presence of salinity, but it is unclear yet how exactly these two pathways intersect. We propose that SnRK2.1, SnRK2.5, SnRK2.9, VCS, and XRN4 control root system architecture under control and salt stress conditions, whereas the role of SnRK2.4 and SnRK2.10 is limited to responses to salinity. mRNA abundance of genes encoding aquaporins Pip2;3 and Pip2;5 and cytochrome P450 protein CYP79B2 depends on subclass SnRK2s; yet whether they are under the control of mRNA decapping remains unknown. Finally, identification of phosphosites in VCS and VCR as SnRK2 targets, and the extensive set of subclass 1 SnRK2-dependent transcripts with roles in root system architecture modifications by salt stress and other biological processes, provide a foundation to further explore the role of SnRK2 phosphorylation in these processes.

**MATERIAL AND METHODS**

**Identification of SnRK2.4 and SnRK2.10 Interactors**

The coding regions of SnRK2.4 and SnRK2.10 were cloned under the CaMV 35S promoter for fusion with G. hirsutum tag in pTi7m24GW2 vector for N- and pH7m34GW2 for C-terminal fusion with Multisite Gateway cloning as described by Van Leene et al. (2015). Arabidopsis (Arabidopsis thaliana) PSBc cell suspension cultures were transformed and TAP of SnRK2.4 and SnRK2.10 protein complexes was performed according to the protocol described by Van Leene et al. (2015). Eluted proteins were identified on linear trap quadrupole (LTQ) Orbitrap Velos with two technical replicates per bait. Proteins identified with at least two peptides were considered as significant. The most abundant background proteins were subtracted, and final list of the putative interactors is presented in Table 1.

**Protein Expression and Purification**

Glutathione-S-transferase fusions were obtained by cloning the full-length coding sequences of SnRK2.4, SnRK2.5, SnRK2.6, and SnRK2.10 into pGEX4T1 and DC2 into pGEX-KG Gateway vector. All constructs were transformed to E. coli BL21 DE3 and their expression was induced for 3 h with 1 mM isopropyl-β-D-galactoside at 18°C. Recombinant proteins were purified with glutathione S-transferase-Sepharose beads (GE Healthcare) as described in Julkowska et al. (2015).

**In Vitro Kinase Activity Assays**

Peptides harboring putative phosphorylation sites were synthesized by GenScript (www.genscript.com). Sequences of used peptides can be found in Table 3. Each peptide (1 μmol) was incubated with 0.1 μmol of recombinant protein kinase in kinase reaction buffer (50 mM Tris-HCl, pH 7.5; 2 mM MgCl2; 1 mM dithiothreitol [DTT]; 0.5 mM ATP; 4 μCi 32P-ATP; 1 μCi 32P-ATP) at 30°C for 30 min. When 20 μl of each reaction was used for direct trapping and collection of the synthet-ic peptides on 8 μg capacity OMIX RP tip (Agilent Technologies). The trapped peptides were eluted in 10 μl 50% (v/v) acetonitrile (ACN), 0.1% (v/v) trifluoroacetic acid (TFA), and a 3–5 μl fraction was dried in a speedvac and reconstituted in 6 μl 2% (v/v) ACN, 0.1% (v/v) TFA for liquid chromatography-mass spectrometry (LC-MS) analysis. The remaining 40 μl of each reaction was used for in-solution digestion. Samples were reduced with 10 μl DTT for 30 min at 60°C followed by alkylation with 20 μl iodoacetamide for 30 min at room temperature in darkness. An overnight digestion with 2 μg trypsin (Sigma) was performed at 37°C, stopped with TFA; peptides were collected with 50% (v/v) ACN, 0.1% (v/v) TFA on 8 μg capacity OMIX RP tip (Agilent Technologies), dried and reconstituted in 6 μl 2% (v/v) ACN, 0.1% (v/v) TFA for the analysis by LC-MS/MS. For the kinase activity assays with full-length protein as a substrate, 0.4 μg of recombinant protein kinase and 2 μg of the substrate were used for the same reactions as with peptides in a total volume of 30 μl, digested with trypsin, collected, and analyzed as described above. MBP was used as a substrate for a positive control of protein kinase activity.

**Mass Spectrometry Analysis**

Mass spectrometry analyses were done with the amaZon Speed ion trap with a Captivempray ion source (Bruker) coupled to an EASY-nLC II (Proxeon, Thermo Fisher Scientific) chromatographic system. Peptide samples were injected and separated with an eluent flow of 300 nL × min−1 on an Acclaim PepMap100 C18 (75 μm × 25 mm, Dionex, Thermo Fisher Scientific) analytical column combined with an Acclaim PepMap100 precolumn (C18 100 μm × 2 mm, Dionex, Thermo Fisher Scientific) using a 30-min gradient of 0% to 50% (v/v) ACN and 0.1% (v/v) formic acid. Peptide precursor ions above a predefined threshold ion count were selected for low-energy collision-induced dissociation to obtain fragmentation spectra of the peptides. Technical replicates were performed with electron-transfer dissociation (ETD). Tandem mass spectrometry (MS/MS) data were processed with Data Analysis software (Bruker), and used for database searching with Mascot software (Version 2.5.1) in a custom-made database containing all SnRK protein kinases, MBP, and the synthetic peptides sequence information. Searches were simultaneously performed on the obtained mass spectrometry data against the Arabidopsis Protein Database (compiled by Max Planck Institute of Biochemistry, Martinsried) to minimize false identifications. Mascot search parameters were as follows: a fixed modification of carbamidomethyl for Cys, variable modification of oxidized Met and Phospho(ST), trypsin with the allowance of one missed cleavage, peptide charge state +2, +3, and +4. Peptide and MS/MS mass error tolerances were 0.3 Da for electrospray ionization-trap or electron-transfer dissociation-trap. For the sample with synthetic peptides no fixed modification was applied. The identified phosphopeptides were verified by manual inspection of MS/MS spectra in the raw data using the Data Analysis software.

**Root System Architecture Assay**

Seeds were surface sterilized with 20 ml dilute bleach and 600 μL 37.5% (v/v) HCl for 3 h followed by 1.5 h in laminar flow to evaporate chlorine gas. Seeds
were stratified in 0.2% (w/v) agar at 4°C in the dark for 72 h. Seeds were germinated on half-strength Murashige-Skoog medium supplied with 0.5% (w/v) Suc, 0.1% (w/v) MES monohydrate, and 1% (w/v) agar with pH 5.8 (adjusted with KOH). Seeds were germinated on vertically positioned plates (70° angle) under long-day conditions (21°C, 70% humidity, 16/8 light/dark cycle). The 4-d-old seedlings of similar main root length were transferred to 0.5× MS media supplemented with 0.75, or 125 mM NaCl. Root System Architecture of 10-d-old seedlings from control and salt stress conditions, respectively, was quantified with Smartroot Software (Lobet et al., 2011). Two independent biological experiments with 20 replicates per condition were performed. Individuals with main root length and lateral root number values outside the 3rd quartile were identified as outliers and removed from dataset. Statistical analysis was performed with ANOVA with experiment number as factor followed with pairwise genotype*treatment comparison by least square means test.

### In-Gel Kinase Activity Assay

Arabidopsis seeds were surface sterilized with 20 mL dilute bleach and 600 μL 37.5% (v/v) HCl for 3 h and then placed for 1.5 h in laminar flow to evaporate chlorine gas. Seeds were stratified for 72 h at 4°C and grown under long-day conditions (21°C, 70% humidity, 16/8 light/dark cycle) in 100 mL liquid media containing 0.5× Murashige-Skoog basal salt, 0.5% (w/v) Suc, 1% (w/v) MES monohydrate, pH 5.8 (KOH) with shaking (120 rpm). The 10-d-old seedlings were treated with 150 mM NaCl in 0.1 M MES monohydrate, pH 5.8 (KOH) with shaking (120 rpm). The 10-d-old seedlings were treated with 150 mM NaCl in 0.1 M MES monohydrate, pH 5.8 (KOH) with shaking (120 rpm). The 10-d-old seedlings were treated with 150 mM NaCl in 0.1 M MES monohydrate, pH 5.8 (KOH) with shaking (120 rpm).

### Statistical Analysis

Statistical analysis of the root system architecture assays was performed with two-way ANOVA in R. A summary of the statistics can be found in Supplemental Datasets S1–S3.

### Accession Numbers

The transcriptomic data from this article has been deposited in the Array Express (http://www.ebi.ac.uk/arrayexpress) under the accession E-MTAB-8073.

### Supplemental Data

The following supplemental materials are available.

#### Supplemental Figure S1
Spectra of the phosphorylated peptides identified in SnRK2.4 and SnRK2.10 TAP experiments.

#### Supplemental Figure S2
Spectra of the phosphorylated synthetic peptides identified in in vitro kinase activity assays.

#### Supplemental Figure S3
Components of SnRK2 subclass 1-regulated 5′ mRNA decay pathways contribute to root development and root system architecture responses to salt stress.

#### Supplemental Figure S4
Expression of VCS (VARICOSE) and XRN4 (5′ EXORIBONUCLEASE 4) in amiRNA lines VCS #2 and VCS#4 and in T-DNA insertion lines xrn4-5 and xrn4-6.

#### Supplemental Figure S5
Rapid activation of SnRK2.4 and SnRK2.10 in Arabidopsis seedlings.

#### Supplemental Figure S6
Salt stress induced changes in mRNA abundance of genes encoding SnRK2 protein kinases.

#### Supplemental Figure S7
Overview of the process of the selection of salt stress regulated genes that are dependent on subclass 1 SnRK2 protein kinases.

#### Supplemental Figure S8
SnRK2 subclass 1 protein kinases regulate gene expression under nonstressed conditions.

#### Supplemental Figure S9
Salt-induced expression of PLASMA MEMBRANE INTRINSIC PROTEINS (PIP2:5, PIP2:3), BETA GLUCOSIDASE 4, CYTOCHROME P450, FAMILY 79, SUBFAMILY B, POLYPEPTIDE 2 (CYP79B2) is dependent on SnRK2 subclass 1 protein kinases signaling.

#### Supplemental Table S1
Protein identification details obtained with the LTQ Orbitrap Velos (Thermo Fisher Scientific) and Mascot Distiller software (version 2.5.0, Matrix Science) combined with the Mascot search engine (version 2.5.0 for SnRK2.4, and version 2.5.1 for SnRK2.10, Matrix Science) using the Mascot Daemon interface and database TAIRplus (Van Leeuwen et al., 2015).

#### Supplemental Table S2
Recombiant SnRK2.4 protein phosphatases MBP, yet is activity is too low to detect its autophosphorylation and phosphorylation of VCS, VCR and DCP2 peptides.

#### Supplemental Table S3
Peptides identified with MS/MS analysis of the in vitro kinase activity assay with SnRK2.4 and MBP as a substrate.

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Supplemental Table S4. Peptides identified with MS/MS analysis of the in vitro kinase activity assay with SnRK2.10 and MBP as a substrate.

Supplemental Table S5. Peptides identified with MS/MS analysis of the in vitro kinase activity assay with SnRK2.5 and MBP as a substrate.

Supplemental Table S6. Peptides identified with MS/MS analysis of the in vitro kinase activity assay with SnRK2.6 and MBP as a substrate.

Supplemental Table S7. Peptides identified with MS/MS analysis of the in vitro kinase activity assay with SnRK2.10 and DCP2 as a substrate.

Supplemental Table S8. List of differentially expressed genes found in Supplemental Table S13.

Supplemental Table S10. List of genes with expression changed in Col-0 upon 1 h treatment with 150 mM NaCl, but not affected in snrk2.4 mutant.

Supplemental Table S11. List of genes with expression changed in Col-0 upon 1 h treatment with 150 mM NaCl, but not affected in snrk2.4/2.10 mutant.

Supplemental Table S12. List of genes with expression changed in Col-0 upon 1 h treatment with 150 mM NaCl, but not affected in snrk2.1/2.4/2.5/2.9/2.10 mutant.

Supplemental Table S13. List of genes which expression was regulated in snrk2.4 mutant, but to a different degree or in an opposite manner than in Col-0.

Supplemental Table S14. List of genes which expression was regulated in snrk2.4/2.10 mutant, but to a different degree or in an opposite manner than in Col-0.

Supplemental Table S15. List of genes which expression was regulated in snrk2.1/4/5/9/10 mutant, but to a different degree or in an opposite manner than in Col-0.

Supplemental Table S16. List of the genes overlapping between our candidate genes acting downstream of SnRK2 subclass 1 protein kinases and transcripts reported to have half-life shorter than 3 h as reported in Narsai et al. (2007).

Supplemental Table S17. List of the genes overlapping between our candidate genes acting downstream of SnRK2 subclass 1 protein kinases and transcripts reported to have half-life shorter than 3 h as reported in Narsai et al. (2007).

Supplemental Table S18. List of the genes overlapping between our candidate genes acting downstream of SnRK2 subclass 1 protein kinases and transcripts reported to be targets of VCS (Sorenson et al., 2018).

Supplemental Table S19. List of the genes overlapping between our candidate genes acting downstream of SnRK2 subclass 1 protein kinases and transcripts reported to be targets of VCS (Sorenson et al., 2018).

Supplemental Table S20. List of the genes overlapping between our candidate genes acting downstream of SnRK2 subclass 1 protein kinases and transcripts reported to be dependent on LSM1 signaling (Perea-Resa et al., 2016).

Supplemental Table S21. List of the primers used for RT-qPCR.

Supplemental Dataset S1. ANOVA tables for RSA assays with snrk2.1/4/5/9/10.

Supplemental Dataset S2. ANOVA tables for RSA assays with VCS amiRNA lines.

Supplemental Dataset S3. ANOVA tables for RSA assays with xrn4-5 and xrn4-6.

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LITERATURE CITED


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Kastenmayer JP, Green PJ (2003) Novel features of the XRN-family in Arabidopsis: Evidence that AtXRN1, one of several orthologs of nuclear Xrn2p/Rat1p, functions in the cytoplasm. Proc Natl Acad Sci USA 97: 13985–13990


Szymanska KP, Polkowski-Kowalczyk L, Lichocka M, Maszkowska J, Dobrowolska G (2019) SNF1-related protein kinases SnRK2.4 and...
SnRK2.10 modulate ROS homeostasis in plant response to salt stress. Int J Mol Sci 20: 143


