Chromatin interacting factor OsVIL2 increases biomass and rice grain yield

Jungil Yang1,†, Lae-Hyeon Cho1,†, Jinmi Yoon1, Hyeryung Yoon1,2, Anht Htet Wai1,2, Woo-Jong Hong1,2, Muho Han1,2, Hitoshi Sakakibara3, Wanqi Liang4, Ki-Hong Jung1,2, Jong-Seong Jeon1,2, Hee-Jong Koh5, Dabing Zhang4 and Gynheung An1,2,*,†

1Crop Biotech Institute, Kyung Hee University, Yongin, Korea
2Graduate School of Biotechnology, Kyung Hee University, Yongin, Korea
3Plant Productivity Systems Research Group, RIKEN Center for Sustainable Resource Science, Tsurumi, Yokohama, Japan
4State Key Laboratory of Hybrid Rice, Shanghai Jiao Tong University-University of Adelaide Joint Centre for Agriculture and Health, School of Life Sciences and Biotechnology, Shanghai Jiao Tong University, Shanghai, China
5Department of Plant Science, Research Institute of Agriculture and Life Sciences, and Plant Genomics and Breeding Institute, Seoul National University, Seoul, Korea

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*Correspondence (Tel +82-31-201-3470; fax +82-31-204-3178; email genean@khu.ac.kr)
†These authors contributed equally to this study.

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Introduction

Increasing grain yield is a major goal in agriculture. In rice (Oryza sativa), this outcome is correlated with the numbers of spikelets and branches produced in a panicle (Zhang et al., 2013). Panicle branching is controlled by LAX PANICLE (LAX), encoding a grass-specific BHLH transcription factor (TF) (Komatsu et al., 2003), and FRIZZY PANICLE (FPZ), encoding an ERF TF (Okawa and Kyoza, 2009). DENSE AND ERECT PANICLE1 (DEP1) regulates CYTOKININ OXIDASE/DEHYDROGENASE2 (OsCKX2) to enhance meristem activity and increase the number of grains per panicle (Huang et al., 2009).

Productivity is also determined by plant architecture. AERRANT PANICLE ORGANIZATION1 (APO1) expands the size of the inflorescence meristem, leading to increases in culm diameters and spikelet numbers (Ikeda-Kawakatsu et al., 2009; Okawa et al., 2010). IDEAL PLANT ARCHITECTURE 1 (IPA1) and WEALTHY FARMER’S PANICLE (WFP) encode SQUAMOSA PROMOTER BINDING PROTEIN-LIKE 14 (OsSPL14), a target of miRNA156 (Jiao et al., 2010; Miura et al., 2010). Enhanced expression of OsSPL14 improves culm thickness and yield (Jiao et al., 2010; Miura et al., 2010).

Cytokinins play a fundamental role in regulating the size of reproductive meristems and number of seeds (Jameson and Song, 2016; Kyoza, 2007). Grain Number per Panicle1 (GNP1) enhances cytokinin levels in the panicle meristems, resulting in more spikelets (Wu et al., 2016). GRAIN NUMBER 1a (Grn1a) is a QTL locus that determine grain yield in rice (Ashikari et al., 2005). This gene encodes OsCKX2, which degrades cytokinin. Reduced OsCKX2 expression increases the level of active cytokinin, resulting in a larger number of tillers and total spikelets per plant (Ashikari et al., 2005; Yeh et al., 2015). Similarly, homologs of OsCKX2 in Hordeum vulgare and Triticum aestivum control panicle size and grain number (Zalewski et al., 2010; Zhang et al., 2012). Expression of OsCKX2 is promoted by LARGER PANICLE (LP) and DROUGHT AND SALT TOLERANCE (DST). The former encodes a Kelch repeat-containing F-box protein found in the endoplasmic reticulum. Mutations in LP are associated with taller plants, thicker culms, larger panicles and greater yield (Li et al., 2011). Perturbing the zinc finger TF DST reduces OsCKX2 expression and boosts cytokinin levels, leading to increased plant height and panicle branching, and a consequent improvement in grain numbers (Li et al., 2013).

Polycomb repressive complex (PRC) regulates crucial processes in development of animals and plants by silencing target genes via histone modification (Jeong et al., 2015; Schuettengruber et al., 2007). For example, PRC2 suppresses target loci by enhancing trimethylation of lysine 27 of histone 3 (H3K27) (Cao et al., 2002). Arabidopsis has three PRC2-like complexes: FERTILIZATION INDEPENDENT SEED (FIS), EMBRYONIC FLOWERING (EMF) and VERNALIZATION (VRN), whereas rice has only Arabidopsis EMF2 homologous proteins, OsEMF2a and OsEMF2b (Kohler and Villar, 2008; Luo et al., 2009; Schubert et al., 2005). The VRN complex interacts with VERNALIZATION INSENSITIVE 3

Summary

Grain number is an important agronomic trait. We investigated the roles of chromatin interacting factor Oryza sativa VIN3-LIKE 2 (OsVIL2), which controls plant biomass and yield in rice. Mutations in OsVIL2 led to shorter plants and fewer grains whereas its overexpression (OX) enhanced biomass production and grain numbers when compared with the wild type. RNA-sequencing analyses revealed that 1958 genes were up-regulated and 2096 genes were down-regulated in the region of active division within the first internodes of OX plants. Chromatin immunoprecipitation analysis showed that, among the downregulated genes, OsVIL2 was directly associated with chromatin in the promoter region of CYTOKININ OXIDASE/DEHYDROGENASE2 (OsCKX2), a gene responsible for cytokinin degradation. Likewise, active cytokinin levels were increased in the OX plants. We conclude that OsVIL2 improves the production of biomass and grain by suppressing OsCKX2 chromatin.

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VIN3 to form PHD-PRC2 complex (De Lucia et al., 2008; Wood et al., 2006), and VIN3 represses FLOWERING LOCUS C (FLC) during vernalization (Sung and Amasino, 2004). The VIN3 and VIN3-like proteins (VIL1 through 4) contain conserved motifs of the PHD finger domain, the fibronectin Type III (FNIII) domain and the VIN3 interacting domain (VID) (Greb et al., 2007; Sung et al., 2006). These proteins function together by binding to each other via the VID domain (Sung et al., 2006). Rice has four VIL proteins (OsVIL1 through 4) that have been shown to interact with each other in a yeast system (Fu et al., 2007). We have previously reported that OsVIL2 binds to O. sativa EMBRYONIC FLOWER 2b (OsEMF2b), a component of rice PRC2 and that PHD-PRC2 complex induces flowering by repressing O. sativa LEAFY COTYLEDON 2 AND FUSCA 3-LIKE 1 (OsLFL1) (Yang et al., 2013).

Here, we demonstrate that OsVIL2 enhances panicle development and plant yield by reducing active cytokinin levels. We showed that OsVIL2 decreases OsCKX2 expression by directly interacting to the promoter region of OsCKX2.

Results

Mutations in OsVIL2 cause reduced yields

We previously described how mutations in OsVIL2 cause late flowering under both short- and long-day conditions (Yang et al., 2013). Here, we observed additional phenotypes from two T-DNA insertion mutants, osvil2-1 and osvil2-2. In both mutant lines, grain number was reduced due to a decrease in primary and secondary branch numbers (Figure 1a-c). This resulted in yield reductions of 32.0% (osvil2-1) and 37.1% (osvil2-2) (Figure 1d). In addition, the mutants displayed abnormal floral organ development that caused low fertility. The presence of these phenotypes suggested that OsVIL2 functions in controlling rice architecture and grain yield.

OsVIL2 OX plants exhibit phenotypes of increased yields

We generated transgenic plants (OsVIL2-OX) that express OsVIL2 cDNA under the maize Ubi promoter. From the 26 independent transformants, we selected two lines with higher expression of OsVIL2 for further analyses. At the seed ripening stage, the OX plants were taller than segregating wild type (WT) (Figure 2a) because the transgenic plants had more and longer internodes (Figure 2b). The diameters of their major culms were also increased (Figure 2c). Total dry weight was also significantly increased in the OX plants when compared with the segregated WT (Figure 2d).

To investigate whether the increase was due to change in cell number or cell size, the basal 0.5 cm region of the first internode was harvested at heading stage. The first internode is the most activity growing region at the stage and the basal region contains rapidly dividing cells. Longitudinal sectioning of the dividing zone of the first internode showed that cells from the transgenic plants were reduced to 62.6% in length but increased to 172% in cell numbers when compared to WT (Figure 3a-c). Cross sections of the region also indicated that culms from OsVIL2-OX plants were thicker when compared with the segregated WT (Figure 3d). The OX plants also had more vascular bundles, sieve tubes and companion cells, as well as increased layers of xylem parenchyma cells (Figure 3d, e).

In addition, the OsVIL2-OX plants developed larger panicles (Figure 4a) and more primary (Figure 4b) and secondary branches (Figure 4c) when compared with the WT. They also had 46.6% (OsVIL2-OX #1) and 57.8% (OsVIL2-OX #2) more grains in the main panicles.

Figure 1 Phenotypes of WT and osvil2 mutants. (a) Comparison of panicles among WT, osvil2-1, and osvil2-2. Scale bar = 5 cm. (b) Number of primary branches on main panicle. (c) Number of secondary branches on main panicle. (d) Total grains per main panicle. Error bars show standard deviations; n = 10. Statistical significance is indicated by * (P < 0.01) and ** (P < 0.001).
main culm (Figure 4d). These OsVIL2-OX phenotypes suggested that OsVIL2 functions to induce cell division and enhance meristem activity at the reproductive stages.

To study whether these phenotypes were reproducible when plants were grown in a large paddy field, we performed 2 years of tests at two different locations. Under field conditions, the same phenotype was maintained as observed in our small-scale experiments, i.e., the OX plants were taller and had larger panicles than the WT. In the first test, grain numbers per panicle were increased by 29.6% and 34.8% in OsVIL2-OX #1 and OsVIL2-OX #2, respectively, and total yield was increased by 28.1%–32.2% over that measured from the WT, although tiller numbers were slightly decreased in the OX plants (Table 1). In the second trial at a different location, the OX plants produced 25.5% and 22.8% more grains per panicle compared with the WT, and total yield was increased to 118.0% and 115.8% of WT (Table 2).

Transcriptome analyses of OsVIL2-OX plants

To determine which genes enhance cell division in the OsVIL2-OX plants, we performed transcriptome analyses using mRNAs prepared from the 0.5 cm basal region of the first internodes sampled from OsVIL2-OX #1 and WT plants at the heading stage. This region is highly meristematic at the stage. Using results from the RNA sequencing analysis, we identified 27 801 annotated genes, among which 1958 had at least twofold higher transcript levels (Table S1) while 2096 had at least twofold lower levels in OsVIL2-OX than in the WT and (Table S2). They can be classified into 20 functional groups by MapMan analysis (Tables S3, S4 and S5). Genes in functional groups of cell division/cell cycle, cell organization, DNA synthesis and protein synthesis/amino acid activation were significantly abundant in the increased genes from OsVIL2-OX plants (Table S3).

Because PHD-PRC2 complex represses target gene expression (De Lucia et al., 2008; Wood et al., 2006), we suspected that transcript levels for the direct targets of our histone-binding gene would be reduced in the OsVIL2-OX plants. We therefore selected down-regulated genes for verifying the results of the RNA sequencing experiment. From that group of genes, we randomly selected four TF genes (LOC_Os01g15900, LOC_Os03g02550, LOC_Os06g19444 and LOC_Os12g03040) and two chromatin interacting factor genes (LOC_Os02g58160 and LOC_Os11g15040). Quantitative real-time RT-PCR analyses confirmed that all were down-regulated in the OsVIL2-OX plants (Figure S1).

OsVIL2 directly regulates the expression of OsCKX2

Cytokinin regulates the size of reproductive meristems and number of seeds by activating cell division and differentiation (Ashikari et al., 2005; Jameson and Song, 2016; Kyozuka, 2007). Because OsVIL2-OX plants exhibited phenotypes of increased grain yield and biomass, we speculated that the phenotypes might be due to elevated cytokinin levels. Interestingly, expression levels of OsCKX2 (LOC_Os01g10110) and OsCKX4 (LOC_Os01g71310), that encode cytokinin-degrading enzymes, were decreased in the OsVIL2-OX plants (Table S2). Because
OsCKX2 is a major QTL that controls grain number (Ashikari et al., 2005), we selected OsCKX2 for further analysis as a potential target of OsVIL2. Quantitative real-time RT-PCR analyses confirmed that the OsCKX2 transcript level was much lower in OsVIL2-OX plants (Figure 5a). Although LP, DST and DEP1 also regulate grain yield (Huang et al., 2009; Li et al., 2011, 2013), we did not analyze them because their transcription was not altered in the OX plants (Figure S2).

Consistent with the role of OsCKX2 in reducing the amount of active cytokinins (Ashikari et al., 2005; Li et al., 2013), we observed that levels of active cytokinins, i.e., N6-(D2-isopentenyl) adenine riboside (iPR), N6-(D2-isopentenyl) adenine ribotides (iPRPS) and trans-zeatin ribotides (tZRPs), were higher in the OX plants than in the WT (Figure 5b).

To examine whether OsVIL2 directly regulates OsCKX2 expression, we performed chromatin immunoprecipitation (ChIP) assays using transgenic plants that express Myc-tagged OsVIL2 protein. Transgenic plants expressing Myc alone were used as the control. Assays using anti-Myc antibody revealed an enrichment of OsVIL2 at the transcript start region of OsCKX2 (Figure 6a, b). As a negative control, we used OsLP and found that it was not enriched in the OsVIL2-Myc transgenic plants (Figure 6c).

Because PHD-PRC2 complex can increase the H3K27me3 levels of target loci (Sung and Amasino, 2004; Sung et al., 2006; Yang et al., 2013), we measured the level of H3K27me3 in OsCKX2 chromatin using H3K27me3 antibodies. In the OsVIL2-OX plants, OsCKX2 chromatin was significantly enriched by the antibodies at the region near the transcript start site (Figure 6d). This result suggested that OsCKX2 expression was reduced in those OX plants by mediating methylation of the H3K27 in its promoter regions.

OsVIL2 interacts with OsEMF2b through the FNIII domain

We have reported previously that OsVIL2 binds to OsEMF2b, a core component of PRC2 complex (Yang et al., 2013). To investigate the region that binds to OsEMF2b, we sub-cloned three conservative motifs in OsVIL2 and fused them to Myc (Figure 7a). Interactions between OsEMF2b and the OsVIL2 fragments were analyzed via co-immunoprecipitation (Co-IP) assays. The analyses showed that the fragment containing FNIII domain binds to OsEMF2b, while the other fragments carrying
either the PHD or VID domain did not interact with the PRC2 subunit (Figure 7b).

Discussion

OsVIL2 represses OsCKX2 expression by chromatin remodelling

Although several genes that regulate grain yield have been identified, little is known about how they are modulated by chromatin remodelling. In this study, we determined that OsVIL2 controls grain yield through the chromatin remodelling of OsCKX2. OsVIL2 is highly homologous to Arabidopsis VIN3 and VILs, which form PHD-PRC2 complexes. Moreover, the conserved motifs of the PHD finger domain, FNIII domain and VID found in Arabidopsis VILs are also present in rice VILs (Greb et al., 2007; Sung et al., 2006).

We observed that OsVIL2 binds to histone H3, supporting its role as a chromatin interacting factor (Yang et al., 2013). We also

Table 1 The first yield test of OsVIL2-OX plants.

<table>
<thead>
<tr>
<th>Traits</th>
<th>Grains per panicle</th>
<th>Panicles per plant</th>
<th>Grains per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>92.9 ± 1.4 (100.0%)</td>
<td>13.6 ± 1.4 (100.0%)</td>
<td>1270.7 ± 47.7 (100.0%)</td>
</tr>
<tr>
<td>OsVIL2-OX #1</td>
<td>120.4 ± 5.1 (129.6%)</td>
<td>12.9 ± 1.5 (94.8%)</td>
<td>1551.2 ± 34.9 (128.1%)</td>
</tr>
<tr>
<td>OsVIL2-OX #2</td>
<td>125.3 ± 2.3 (134.8%)</td>
<td>12.6 ± 0.9 (92.6%)</td>
<td>1574.7 ± 32.3 (132.2%)</td>
</tr>
</tbody>
</table>

Plants were grown in paddy field at Gunwi, Korea (36°24'N) in 2014 at a spacing of 15 cm × 30 cm, with three plants per hill. The plot area was 5.4 m². Values are means with standard deviations of three replications.

Table 2 The second yield test of OsVIL2-OX plants.

<table>
<thead>
<tr>
<th>Traits</th>
<th>Grains per panicle</th>
<th>Panicles per plant</th>
<th>Grains per plant</th>
<th>Grain weight per plant</th>
<th>Fertility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>136.7 ± 11.6 (100.0%)</td>
<td>14.7 ± 1.7 (100.0%)</td>
<td>1997.7 ± 148.4 (100.0%)</td>
<td>42.4 ± 3.1 (100.0%)</td>
<td>89.3 ± 5.1</td>
</tr>
<tr>
<td>OsVIL2-OX #1</td>
<td>171.6 ± 20.5 (125.5%)</td>
<td>13.9 ± 1.5 (94.6%)</td>
<td>2356.9 ± 193.6 (118.0%)</td>
<td>52.1 ± 4.3 (122.9%)</td>
<td>86.0 ± 5.0</td>
</tr>
<tr>
<td>OsVIL2-OX #2</td>
<td>167.8 ± 13.3 (122.8%)</td>
<td>13.8 ± 1.5 (93.9%)</td>
<td>2314.3 ± 158.0 (115.8%)</td>
<td>50.7 ± 3.5 (119.6%)</td>
<td>85.6 ± 3.5</td>
</tr>
</tbody>
</table>

Plants were grown in paddy field at Yongin, Korea (37°14'N) in 2017 at a spacing of 30 cm × 30 cm, with three plants per hill. The plot area was 9 m². Values are means with standard deviations of three replications.

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showed that OsVIL2 binds to the FnIII domain of OsEMF2b, which is a homologue of Drosophila Sat(2)12 and a core member of PRC2 (Hennig and Derkacheva, 2009). In Arabidopsis, the complex between VILs and PRC2 core proteins provides the trimethylation activity to target chromatin and influences vegetative development, flowering time and floral organ development (Conrad et al., 2014; Schonrock et al., 2006; Yang et al., 2013; Yoshida et al., 2001). Because OsVIL2 also binds to EMF2b and histone H3, it is likely that the former forms a complex with core PRC2 via EMF2b. This complex would function in histone methylation because the level of H3K27me3 in the OsCKX2 promoter region was changed in the OsVIL2-OX plants. Further studies are needed to elucidate molecular mechanisms how the OsVIL2-PRC2 complex associates to the target chromatin in rice.

OsVIL2 enhances grain yield by increasing cytokinin concentrations

The balance between cytokinin synthesis and catabolism is an important element in controlling meristem activity and grain yield (Mok and Mok, 2001; Sakakibara, 2006). The CKX protein has a critical role in controlling cytokinin levels in the shoot apical meristem (SAM). For example, overexpression of CKX2 retards the formation of leaf and flower primordia in Arabidopsis (Werner et al., 2003). In contrast, cks3 mutation enhances cytokinin concentrations in SAM and enlarges the meristem (Bartrina et al., 2011).

In rice, LONELY GUY (LOG) encodes a phosphoribohydrolase that converts cytokinin nucleotides to free-base forms such as iPR and IZR, which are active cytokinins. The log mutants have fewer branches and spikelets (Kurakawa et al., 2007). By contrast, a reduction in OsCKX2 expression results in the accumulation of active cytokinin and a greater number of spikelets, suggesting that increases in endogenous cytokinin levels in the inflorescences causes them to form large meristems (Ashikari et al., 2005). In this study, we showed that the chromatin interacting factor OsVIL2 elevates cytokinin levels by suppressing OsCKX2 expression. Activated expression of OsCKX4 reduces cytokinin levels, and those plants are shorter and produce less panicle branches and grains (Gao et al., 2014). We did not study OsCKX4 because it has a major role in modulating crown root development (Gao et al., 2014). However, we do not rule out a possibility that OsCKX4 is also a target of OsVIL2.

Cytokinin promotes cell division and proliferation. We showed that cell numbers were dramatically increased at the basal part of the first internode in OsVIL2-OX plants compared with the WT. RNA sequencing analysis of the basal part revealed that expression levels of a large number of genes that function in cell division and cell cycles, as well as those involved in synthesis of DNA, and protein were elevated in the OsVIL2-OX plants. This observation suggests that elevated level of cytokinins in the OsVIL2-OX plants enhanced meristem activity and cell division that resulted in increase in plant biomass and yield.

The RNA sequencing analysis also revealed that WFP (LOC_Os08g39890) and TERMINAL FLOWER 1 (TFL1)/CENTRORADIALIS (CEN)-like genes (RCN1; LOC_Os11g05470 and RCN2; LOC_Os02g32950) were up-regulated in the OsVIL2-OX plants. In previous studies, overexpression of WFP increases total grain number per panicle by producing more primary branches (Miura et al., 2010). However, overexpression of RCN1 increases grain productivity by producing more secondary and tertiary branches rather than primary branches (Nakagawa et al., 2002). In the OsVIL2-OX plants, the number of both primary and secondary branches was increased compared with the WT. It has been suggested that fine-tuning of SPL and RCN regulates vegetative and reproductive branching in rice (Wang et al., 2015). Therefore, up-regulation of these genes in the OsVIL2-OX plants might play an important role in increasing total grain yield by modulating the activities of inflorescence and branch meristems.

OsVIL2 modulates plant architecture

To increase productivity, breeders have been selecting semi-dwarf varieties that grow well without chemical fertilizers (Asano et al., 2007; Ashikari et al., 2002). Tall plants generally are not favoured because they are susceptible to lodging. However, tall, sturdy stems and fewer tillers are considered important characteristics of ideal plant architecture, or IPA (Khush, 1995; Virk et al., 2004). Both IPA1 and WFP contribute to IPA and increased grain yield (Jiao et al., 2010; Miura et al., 2010). Rice cultivars containing IPA1/WFP are tall and have fewer tillers but more branches and spikelets. Their thicker culms also improve their resistance to lodging (Jiao et al., 2010; Miura et al., 2010). Another effective QTL is STRONG CULM2 (SCM2) (Ookawa et al., 2010). SCM2-carrying cultivars have sturdier culms and more spikelets that lead to higher yields and better lodging resistance (Ookawa et al., 2010).

**Figure 5** OsCKX2 transcription and cytokinin concentrations in OsVIL2-OX, mutant and WT plants. (a) Transcript levels in first internodes from WT and OsVIL2-OX #1 were measured by quantitative real-time PCR. Y-axis, relative transcript level of OsCKX2 compared with that of Ubi. Error bars indicate standard deviations; n = 3 or more. (b) Cytokinin levels in first internodes of WT and OsVIL2-OX #1. iPRPs, N6-(2-isopentenyl) adenine ribotides; tZRPs, trans-zeatin ribotides; iPR, N6-(2-isopentenyl) adenine riboside; tZR, trans-zeatin; tZ, trans-zeatin riboside; iP, N6-(2-isopentenyl) adenine. Error bars indicate standard deviations; n = 3 or more. Statistical significance is indicated by ** (P < 0.001).
We also demonstrated here that increased expression of OsVIL2 results in a phenotype of tall, thicker culms, greater branching and higher grain numbers. Therefore, this gene could be used for achieving IPA in molecular breeding programs.

Experimental procedures

Plant materials and growth

The T-DNA mutant lines were isolated from a T-DNA tagging line (Oryza sativa japonica cv. Dongjin and Hwayoung) (Jeon et al., 2000; Jeong et al., 2002). Their flanking sequences were determined by inverse PCR (An et al., 2003; Jeong et al., 2006; Ryu et al., 2004). We previously described the T-DNA insertional mutants osvil2-1 and osvil2-2 as well as transgenic plants that express OsVIL2-Myc (Yang et al., 2013). All plants were grown either in the greenhouse or in certified genetically modified organism (GMO) fields at Yongin and Gunwi, Korea. For the field tests, three seedlings were planted per hill, at a spacing of 15 × 30 cm, as reported previously (Lee and An, 2015). Whole plants including roots were harvested at heading stage from the paddy. Roots were carefully washed to remove the soil. Plants were dried at 65 °C for 5 d before measuring dry weight.

Vector construction and plant transformation

The full-length OsVIL2 cDNA clone was isolated by PCR, using two primers: 5'-AAGCTTCAATTCGCCATG GATCCACC-3' and 5'-ACTAGTATGCAAGT TCCATGCA-3'. An amplified fragment was digested with restriction enzymes HindIII and SpeI, and inserted into the pGA3426 vector under the control of the maize ubiquitin 1 promoter (Kim et al., 2009). The construct was then transferred into Agrobacterium tumefaciens LBA4404 by the freeze-thaw method (An et al., 1988). Procedures for transforming rice via Agrobacterium-mediated co-cultivation were described previously (Jeon et al., 1999; Yoon et al., 2014).

RNA extraction and RT-PCR analyses

Total RNA was isolated using RNAiso Plus (Takara, Shiga, Japan; http://www.takara-bio.com). First-strand cDNA was synthesized with 2 μg of total RNA and Moloney murine leukaemia virus reverse transcriptase (Promega, Madison, WI, USA; http://www.promega.com). Synthesized cDNA was prepared from leaf blades, and quantitative real-time RT-PCR was performed with a Rotor-Gene 6000 (Corbett Research, Sydney, Australia; http://www.corbettlife_science.com), following protocols reported earlier (Cho

Figure 6 Chromatin immunoprecipitation assay of OsCKX2 chromatin with OsVIL2-Myc. (a) Genomic structure of OsCKX2 and OsLP. Tested regions are numbered. (b) ChIP analysis of OsVIL2 enrichment on OsCKX2 chromatin. OsVIL2-Myc epitope-tagged transgenic lines were used to detect enrichment. Actin chromatin served as control. Samples from OsVIL2-Myc plants are indicated in red, while those from control plants expressing only Myc are in blue. (c) ChIP analysis of OsVIL2 enrichment on OsLP1 chromatin. OsVIL2-Myc epitope-tagged transgenic lines were used to detect enrichment. Actin chromatin served as control. Samples from OsVIL2-Myc plants are indicated in red, while those from control plants expressing only Myc are in blue. (d) Analysis of H3K27me3 level on OsCKX2 chromatin in WT (blue) and OsVIL2-OX #1 (red) using antibodies against H3K27me3. Actin chromatin served as control. Error bars show standard deviations; n = 3.

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generate clean-read datasets by removing the adaptor sequences, reads with >5% ambiguous bases (noted as N), and low-quality reads that contained more than 20% of bases with qualities of <20. The clean reads were then aligned to the rice japonica genome (version: Tigr 7.0) using the Tophat program (v2.0.11) under the following parameters: -a 10 -m 0 -i 31 -l 500000 -G (Trapnell et al., 2012). The DSEQ algorithm was applied to filter the differentially expressed genes. Genes with significantly different expression were determined by FDR < 0.05 and fold changes of >2 or <0.5 in two samples (Anders and Huber, 2010).

**GO analysis**

The GO information of differently expressed genes were retrieved from the rice oligonucleotide array database (now available at http://ricephylogenomics-khu.org/ROAD/analysis/go_enrichment.shtml) (Cao et al., 2012). Fold-enrichment values were calculated by dividing the query number by the query expected value. We selected GO terms with a fold-enrichment greater than 2 and a hyper-geometric P-value below 0.05. Visualization of GO terms was done by EXCEL software, and Illustrator software was used to polish GO terms. Functional information of differentially expressed genes was analyzed by the MapMan toolkit (3.6.0RC1), which has been frequently used for functional classification of transcriptome data (Thimm et al., 2004).

**Measurements of cytokinin levels**

Extractions and determinations of cytokinins from the division region of the first internodes of the WT and OsVIL2-OX #1 plants were performed with an UPLC-MS/MS (AQITY UPLC™ System/Quattro Ultima Pt; Waters) and ODS column (AQUITY UPLC BEH C18, 1.7 μm, 2.1 × 100 mm; Waters), as described previously (Kojima et al., 2009).

**Co-immunoprecipitation assay**

The Co-IP assays were performed as reported earlier (Cho et al., 2016; Yoon et al., 2017). Briefly, fusion molecules were co-expressed in rice Oc cell protoplasts. Afterwards, fusion proteins were extracted in IP buffer [75 mM NaCl, 50 mM Tris-HCl (pH 7.5), 5 mM EDTA, 1% Triton X-100, 1 mM dithiothreitol, 1 mM phenyl-methanesulfonylfluoride, 2 mM NaF, 20 mM MG132, and an appropriate amount of Protease inhibitor cocktail (Roche)]. Expressed proteins were immuno-precipitated with anti-HA mouse monoclonal antibodies (12CA5; Roche, Mannheim, Germany, http://www.roche.com) conjugated with A and G agarose beads (Millipore, Billerica, MA, USA, http://www.emdmillipore.com). For protein detection, we used horseradish peroxidase (HRP)-conjugated anti-Myc monoclonal antibody (#2404; Cell Signaling) and anti-HA monoclonal antibody (#2999; Cell Signal).

**Chromatin immunoprecipitation analysis**

Transgenic plants expressing OsVIL2-Myc were used for ChIP analysis, as described previously (Yang et al., 2013; Yoon et al., 2017), with the anti-Myc monoclonal antibody (Cell Signaling; #2276) and the anti-H3K27me3 monoclonal antibody (Millipore; 07-449). The assays were performed as reported earlier (Haring et al., 2007). Primer sequences are listed in Table S6. All assays were performed at least three times from two biological replicates.

**Statistical analyses**

The P values were calculated using one-way analysis of variance (ANOVA; Tukey HSD test) for the test groups with R program (Cohen and Cohen, 2008).
OsVIL2 increases biomass and grain yield in rice


Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1 Confirmation of RNA sequencing by quantitative real-time PCR.

Figure S2 Transcript levels of LP, DST and DEP1 in WT and OsVIL2-OX plants.

Table S1 Differentially up-regulated genes in OsVIL2-OX.

Table S2 Differentially down-regulated genes in OsVIL2-OX.

Table S3 Classification of up- and down-regulated genes in OsVIL2-OX. The functional groups that are significantly abundant in the increased genes are indicated in blue.

Table S6 Primers used in this study.