Disruption of the mRNA m^{6}A writer complex triggers autoimmunity in Arabidopsis

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ABSTRACT

Distinguishing self from non-self is crucial to direct immune responses against pathogens. Unmodified RNAs stimulate human innate immunity, but RNA modifications suppress this response. mRNA m^6A modification is essential for *Arabidopsis thaliana* viability. However, the molecular basis of the impact of mRNA m^6A depletion is poorly understood. Here, we show that disruption of the Arabidopsis mRNA m^6A writer complex triggers autoimmunity. Most gene expression changes in m^6A writer complex *vir-1* mutants grown at 17°C are explained by defence gene activation and are suppressed at 27°C, consistent with the established temperature sensitivity of Arabidopsis immunity. Accordingly, we found enhanced pathogen resistance and increased premature cell death in *vir-1* mutants at 17°C but not 27°C. Global temperature-sensitive mRNA poly(A) tail length changes accompany these phenotypes. Our results demonstrate that autoimmunity is a major phenotype of mRNA m^6A writer complex mutants, which has important implications for interpreting this modification's role. Furthermore, we open the broader question of whether unmodified RNA triggers immune signalling in plants.

INTRODUCTION

Distinguishing self from non-self is crucial to ensuring organisms specifically target immune responses against pathogen infection. RNA modifications provide one layer by which this distinction is made in humans (Freund *et al*, 2019; Karikó *et al*, 2005). Katalin Karikó, Drew Weissman and colleagues revealed that unmodified RNA stimulates the mammalian innate immunity system by activating the Toll-like receptors (TLRs) TL3, TL7 and TL8, but incorporating modified nucleosides into RNA ablated this activity (Karikó *et al*, 2005). Consistent with this, modified nucleosides have been critical in mRNA therapeutics development, and the first mRNA-based vaccines for COVID-19 were based on 1-methyl pseudouridine-containing mRNA (Karikó, 2021). A broader set of factors beyond TLRs function in RNA sensing in humans using RNA structure (including modifications), localisation and availability to distinguish self from non-self (Bartok & Hartmann, 2020). Precision in this process is important because chronic activation of nucleic acid sensing pathways in humans is associated with autoimmune and autoinflammatory conditions (Junt & Barchet, 2015).

The most abundant internal modification of mRNA is the methylation of adenosine at the N6 position (m^6A) (Murakami & Jaffrey, 2022). Null mutations that eliminate the activity of the corresponding N6 methyladenosine methyltransferase METTL3 are embryonically lethal in mouse, demonstrating that this modification can play essential roles in biology (Geula *et al*, 2015). A complex of proteins functions with METTL3 to modify mRNA. Orthologs of the human writer complex components, METTL3, METTL14, VIRILIZER, ZC3H13, WTAP and HAKAI, are conserved in Arabidopsis and required for mRNA m^6A modification (Růžička *et al*, 2017; Zhang *et al*, 2022; Shen *et al*, 2016). Arabidopsis null mutations in each of these components (except the HAKAI and ZC3H13 orthologs) are not viable, and where they exist, hypomorphic alleles have pleiotropic developmental defects (Růžička *et al*, 2017; Shen *et al*, 2016; Wong *et al*, 2023; Zhang *et al*, 2022). In humans and Arabidopsis, m^6A is predominantly written into the terminal exon of mRNA in a preferred context characterised by the DRm^6ACH consensus sequence (Parker *et al*, 2020; Murakami & Jaffrey, 2022).

Reader proteins recognise RNA m^6A modifications and ultimately influence mRNA processing and fate (Zaccara & Jaffrey, 2024, 2020). The best-characterised m^6A reader proteins have a YTH domain, which binds m^6A through a cage of aromatic amino acids. Plants and apicomplexans are unique with respect to m^6A readers because the conserved CPSF30 component of the cleavage and polyadenylation complex, which binds the AAUAAA poly(A) signal (Chan *et al*, 2014; Schönemann *et al*, 2014), has a YTH domain (Stevens *et al*, 2018). Consistent with this, a major impact of m^6A loss on pre-mRNA processing in Arabidopsis writer

complex mutants is disrupted poly(A) site usage (Parker *et al*, 2020, 2022; Wong *et al*, 2023). Not all m^6A effects are mediated by YTH reader domains. m^6A can affect RNA structure (Roost *et al*, 2015; Kierzek & Kierzek, 2003) and, through an m^6A switch mechanism, influence the association of specific RNA-binding proteins with transcripts in an m^6A-dependent manner (Korn *et al*, 2021; Wu *et al*, 2018; Liu *et al*, 2015).

A multilayered innate immunity system mediates defence against pathogens in flowering plants (Locci & Parker, 2024). The first layer consists of trans-membrane receptor proteins called pattern-recognition receptors (PRRs) that detect pathogens in the external environment and signal an immune response known as pattern-triggered immunity (PTI). The second layer comprises networks of proteins that detect pathogen effectors and their activity inside plant cells and is known as effector-triggered immunity (ETI). ETI is mainly mediated by nucleotide binding/leucine-rich repeat (NLR) receptors. Cross-talk between PTI and ETI potentiates the immune response (Yuan *et al*, 2021; Ngou *et al*, 2021; Tian *et al*, 2021; Pruitt *et al*, 2021). The diverse immune receptors converge on shared signalling complexes, such as those containing EDS1, to promote an immune response (Locci & Parker, 2024). In cells infected by pathogens, this can trigger programmed cell death, called the hypersensitive response. Immune responses in neighbouring cells are also activated, but the gene expression pattern differs from those in infected cells (Tang *et al*, 2023; Jacob *et al*, 2023). A concentration gradient of the hormone salicylic acid (SA) between the sites of infection and neighbouring cells controls the hypersensitive response and the massive expression of defence genes such as *PATHOGEN RESPONSIVE 1* (*PR1*) in surrounding cells and systemic acquired resistance in distal tissues (Betsuyaku *et al*, 2018; Fu *et al*, 2012b; Zeier, 2021).

PRRs and NLRs are encoded by some of the largest and most rapidly evolving gene families in plants (Barragan & Weigel, 2021). This diversity corresponds to selective pressure not only for pathogen defence but also to dampen immune responses in the absence of infection, reflecting trade-offs between the benefits of disease resistance and the costs of sustained immune responses on development. Like humans, plants can develop autoimmune conditions (Alcázar & Parker, 2011; van Wersch *et al*, 2016; Freh *et al*, 2022; Wan *et al*, 2021). In Arabidopsis, these manifest as compromised development and premature cell death, visible as leaf lesions. Some of the clearest examples of autoimmunity emerge in crosses between different Arabidopsis accessions (Bomblies *et al*, 2007; Wan *et al*, 2021). This phenomenon, observed in the first or later generations of plant hybrids, is called hybrid necrosis because of the severe pleiotropic symptoms that compromise development and viability (Bomblies & Weigel, 2007). A recurring explanation for hybrid necrosis is simple non-compatible interactions between specific NLRs or other defence genes that activate immune response

pathways (Wan *et al*, 2021). Naturally occurring genetic variation (Todesco *et al*, 2010) or induced mutations (van Wersch *et al*, 2016; Freh *et al*, 2022) also trigger Arabidopsis autoimmunity. For example, gain of function mutations that either stabilise the expression or autoactivate NLRs can cause autoimmunity (Zhang *et al*, 2003; Bonardi *et al*, 2012), and so can the disruption of signalling pathways that are either involved in or sensed by defence responses (van Wersch *et al*, 2016). A characteristic of Arabidopsis autoimmunity is that it can be suppressed by elevated temperature or relatively high humidity, and this property has facilitated the study of autoimmune genotypes (Alcázar & Parker, 2011).

Although the Arabidopsis mRNA m^6A writer complex is essential for viability, the gene expression changes that explain this are unknown. Here, we asked what groups of genes are affected when the mRNA m^6A writer complex is disrupted. We discovered that immune response genes comprise the major class of altered gene expression, but consistent with the temperature-sensitive nature of Arabidopsis immunity, this response was suppressed when plants were grown at elevated temperatures. Furthermore, Arabidopsis mRNA m^6A writer complex mutants display temperature-sensitive increased resistance to pathogen infection and increased levels of premature cell death. Therefore, autoimmunity is a major phenotype of Arabidopsis mRNA m^6A writer complex mutants. In contrast to cases of hybrid necrosis and some other autoimmune mutants, visible developmental defects of mRNA m^6A writer complex mutants were not rescued by growth at elevated temperatures, revealing that the impact of defective mRNA m^6A modification on autoimmunity and development is separable. Therefore, as with humans, RNA modifications in Arabidopsis may contribute to distinguishing self from non-self. Our findings suggest that uncovering how disruption of the mRNA m^6A writer complex triggers defence gene expression is fundamental to understanding this RNA modification's role in plant biology.

RESULTS

Immune gene expression is activated in mRNA m^{6}A writer complex mutants

To understand the roles of mRNA m^{6}A in Arabidopsis, we asked what groups of genes were most affected by the loss of function of the m^{6}A writer complex protein, VIRILIZER. We previously characterised gene expression changes in *vir-1* mutants using a combination of Illumina RNA sequencing (RNA-seq) and Oxford Nanopore Technologies direct RNA sequencing (ONT DRS) (Parker *et al*, 2020). We analysed three genotypes with different VIR activity: a wild-type Col-0 control, a hypomorphic Arabidopsis *vir-1* mutant defective in *VIR* function, and a complementation line expressing VIR fused to Green Fluorescent Protein (GFP) (VIR complemented; VIRc) that partly restores VIR activity in the *vir-1* mutant background (Růžička *et al*, 2017; Parker *et al*, 2020). For each genotype grown in sterile conditions at 22°C, we sequenced RNA purified from seedlings of at least six biological replicates with Illumina RNA-seq and four with ONT DRS (Supplementary file 1).

Using the Illumina RNA-seq data, we identified differentially expressed genes between *vir-1* and WT Col-0 by fitting a quasi-likelihood model in edgeR (Chen *et al*, 2016) (threshold: adj.p < 0.001, log2FC > 2.0). We found 806 genes significantly upregulated in *vir-1* compared to Col-0 and 349 genes significantly downregulated (Supplementary Table 1). We examined GO (gene ontology) term distribution among the differentially expressed genes using gProfiler (Kolberg *et al*, 2023). The most significantly enriched GO terms were related to response to external stimuli and defence. For example, 92 of the 597 upregulated genes with GO term annotation were annotated with the biological process 'defense response' (GO:0006952), a significant enrichment (adjusted p = 1.32×10^{-8}) compared to the background of all genes (Figure 1A, Supplementary Table 2).

To examine the global expression trends for defence-related genes, in a different way, we identified 1033 genes that included 'defence' or 'defense' in their TAIR annotation description (Reiser *et al*, 2024). Of these genes, 86 were differentially expressed in at least one condition. Plotting the zero-centred fold change of these genes shows the extent of expression recovery in the VIRc complementation line (Figure 1B). For example, expression of the defence marker gene *PR1* (AT2G14610) was 311-fold (8.28 log2FC) higher in *vir-1* than Col-0 but restored to similar levels as Col-0 in the VIRc complementation line. The upregulation of *PR1* in *vir-1* is also detected in the orthogonal ONT DRS data (Figure 1C-E). We next asked if other m^{6}A writer mutants had elevated *PR1* expression. We analysed ONT DRS data of *fip37-4* mutants that disrupt the Arabidopsis m^{6}A writer complex ortholog of WTAP (Parker *et al*, 2022). Genes which are significantly upregulated in *fip37-4* mutants are

significantly enriched for GO terms related to defence (Supplementary Table 3). Like *vir-1* mutants, *fip37-4* mutants have elevated *PR1* expression (Figure 1F). In contrast, *PR1* is not upregulated in *fiona1* mutants that disrupt the Arabidopsis N6 methyladenosine methyltransferase METTL16 ortholog that adds m^6A to U6 snRNA (Parker *et al*, 2022) (Figure 1C). We conclude that a phenotype of Arabidopsis mRNA m^6A writer complex mutants is the upregulation of genes involved in defence signalling.

Loss of the mRNA m^6A writer complex triggers temperature-sensitive autoimmunity

The upregulation of defence response genes in *vir-1* raised the question of whether autoimmunity might explain the gene expression changes and pleiotropic developmental phenotypes of mRNA m^6A writer complex mutants. A hallmark of Arabidopsis autoimmunity is its temperature sensitivity, with autoimmune phenotypes suppressed at elevated ambient temperatures (Alcázar & Parker, 2011). Therefore, to address whether the gene expression changes we detected in *vir-1* mutants reflected an autoimmune response, we compared the gene expression profiles of *vir-1* and WT Col-0 seedlings grown in sterile conditions at 17°C and 27°C. We used a combination of Illumina RNA-seq and ONT DRS to analyse gene expression. We performed four biological replicates with each RNA sequencing technology, genotype and temperature treatment. The resultant sequencing statistics are detailed in Supplementary file 1.

We analysed the Illumina RNA-seq data using a quasi-likelihood model (glmQLFit) in edgeR (Chen *et al*, 2016) and identified genes differentially expressed between *vir-1* and WT Col-0 at each temperature. This revealed 1215 genes which were significantly upregulated (adj.p < 0.001, log2FC > 2.0) in *vir-1* at 17°C (Supplementary Table 4). Remarkably, 91% of these genes (1103) were not significantly upregulated in *vir-1* at 27°C (Figure 2A), revealing that most gene expression changes in *vir-1* are temperature-sensitive. Principal component analysis (PCA) separates the biological replicates by genotype and temperature. The first component, which explains 40% of the variance, captures gene expression changes specific to *vir-1* at 17°C. In contrast, *vir-1* and Col-0 are indistinguishable at 27°C in this component (Figure 2B). Likewise, correlation matrix analysis reveals that the gene expression features of *vir-1* mutants grown at 17°C are the most distinct among all the datasets (Figure 2C). We found elevated expression of *PR1* in *vir-1* grown at 17°C, just as we had previously seen at 22°C, but *PR1* expression was at similar levels to WT Col-0 in *vir-1* grown at 27°C (Figure 2D). We also detected this differential *PR1* expression pattern with orthogonal ONT DRS data (Supplementary Figure 2A) and RT-qPCR (Supplementary Figure 2B).

We used a generalised linear model (GLM) to model all conditions simultaneously and identify differential gene expression specific to *vir-1* at 17°C. The GLM design contrasts *vir-1* at 17°C minus the average of Col-0 at 17°C and 27°C and *vir-1* at 27°C. This model identified 931 genes with significantly increased expression (adj.p < 0.001, log2FC>2.0) in *vir-1* at 17°C compared to the other conditions (Supplementary Figure 2C, Supplementary Table 5). GO-term analysis revealed that the biological processes most significantly enriched in genes upregulated in *vir-1* at 17°C were related to defence responses (Figure 2E, Supplementary Table 6). The defence annotation GO terms were similar in describing the gene expression changes previously detected in *vir-1* grown at 22°C (Supplementary Figure 2D). As an orthogonal approach, we analysed protein domain enrichment using DAVID (Sherman *et al*, 2022) (Supplementary Table 6). The most significantly enriched protein domains in genes upregulated in *vir-1* at 17°C were RLP23-like, which is found in receptor-like kinases that function as PRR proteins (15-fold enrichment) and Defensin_plant, a domain found in highly expressed marker proteins of defence (10-fold enrichment). Next, we used a different approach to ask how defence gene expression was affected by temperature using the GLM analysis. We plotted the zero-centred log2FC normalised gene expression of 136 genes with defence/defense included in their TAIR annotation in *vir-1* at 17°C compared to other conditions. This analysis reveals that the expression level of most genes with a TAIR defence/defense annotation in *vir-1* at 17°C is at WT Col-0 levels when *vir-1* mutants are grown at 27°C (Figure 2F).

To determine whether the major defence gene expression differences observed in *vir-1* at 17°C compared to all other conditions might be explained by overlooked pathogen contamination of our experimental material, we examined our RNA-seq data for non-Arabidopsis sequences. We used all *vir-1* Illumina RNA-sea data to produce a *de novo* transcriptome assembly and searched the resulting contigs against the GenBank NR (non-redundant) database using BLASTP (Camacho *et al*, 2009). No significant enrichment of plant pathogen sequences was found in *vir-1* 17°C samples (Supplementary Table 7).

In summary, by exploiting the established temperature sensitivity of Arabidopsis immunity, we discovered that the major annotation terms associated with the upregulated genes in *vir-1* mutants at 17°C are related to defence. Therefore, at the gene expression level and strikingly dependent on temperature, we conclude that autoimmunity is a major phenotype of the Arabidopsis mRNA m^6A writer complex mutant, *vir-1.*

Genes that function in diverse aspects of immunity are upregulated in *vir-1* mutants

Given the global trend of defence gene activation in *vir-1* mutants, we next analysed individual gene expression changes to understand what type of defence genes were affected. Expression of mRNA encoding the master defence transcription factor SARD1 (Sun *et al*, 2015; Wang *et al*, 2011) was upregulated (AT1G73805: log2FC 4.0) in *vir-1* at 17°C but not 27°C, consistent with the established temperature sensitivity of *SARD1* transcription (Kim *et al*, 2022) (Figure 3A and Supplementary Figure 3A). The expression of mRNA encoding the FLS2 receptor, which detects the bacterial flagellin flg22 peptide (Gómez-Gómez & Boller, 2000) and is one of the best-characterised Arabidopsis PRR proteins, was upregulated in *vir-1* at 17°C (AT5G46330: log2FC 3.0) but not at 27°C (vir_27 vs Col-0_27: log2FC 1.3) (Figure 3B and Supplementary Figure 3B). We detected the upregulation of 15 annotated NLRs - 13 TIR-NLRs, one CC-NLR (*LOV1*) and one RPW8-NLR (*HR4*) at 17°C but not 27°C (Supplementary Table 8). For example, the TIR-only *TX0* was upregulated (AT1G57630: log2FC 4.1) (Figure 3C and Supplementary Figure 3C). TX0 can hydrolyse nucleic acids, particularly RNA, and synthesise 2',3',-cAMP/cGMP molecules that ultimately signal cell death in the hypersensitive response (Yu *et al*, 2022).

We next asked whether genes previously associated with Arabidopsis autoimmunity were misregulated in *vir-1.* The TIR-NLR *RPS6* (AT5G46470) is recurrently associated with autoimmunity. For example, the extreme phenotypes of Arabidopsis nonsense-mediated RNA decay (NMD) and mitogen-activated kinase mutants have been attributed to *RPS6* (Gloggnitzer *et al*, 2014; Takagi *et al*, 2020), although the mechanisms involved are not understood (Gloggnitzer *et al*, 2014; Takagi *et al*, 2020; Parker *et al*, 2021b). *RPS6* expression is not significantly altered in *vir-1* RNA-seq data, but ONT DRS analysis indicates that the TIR-only gene located downstream of the *RPS6* locus is upregulated (Parker *et al*, 2021b) (Supplementary Figure 3D). The TIR-NLR *SNC1* has been used as a model to understand autoimmune signalling (Zhu *et al*, 2010); *SNC1* was not significantly upregulated in *vir-1* at 17°C (log2FC 1.22), but *SIDEKICK3*, a TIR-NLR required for *SNC1*-mediated autoimmunity (Dong *et al*, 2018), is one of the most upregulated genes (log2FC 8.32) in *vir-1* at 17°C (Supplementary Table 8). Finally, we examined *ACD6,* which encodes a multipass transmembrane protein with intracellular ankyrin repeats, that mediates a trade-off between growth and defence (Chen *et al*, 2023). First identified in lab-based mutant screens (Rate *et al*, 1999; Lu *et al*, 2003), high-activity *ACD6* alleles are frequently found in natural Arabidopsis accessions (Świadek *et al*, 2017; Zhu *et al*, 2018; Todesco *et al*, 2010). *ACD6* is upregulated in *vir-1* at 17°C (log2FC 6.27), but the expression level is similar to WT Col-0 in *vir-1* grown at 27°C (Figure 3D and Supplementary Figure 3E). We asked whether the changes in gene expression between *vir-1* and *acd6* mutants were related by re-analysing a recently published

acd6-1 Illumina RNA-seq dataset (Fabian *et al*, 2023). We found a subset of differentially expressed genes overlap between these two mutants; 205 upregulated genes and 21 down-regulated genes in common (Figure 3E). However, 931 genes are uniquely upregulated in *acd6-1* and 701 genes are uniquely upregulated in *vir-1* at these thresholds (adj.p < 0.001, log2FC>2.0), indicating that the misregulation of *ACD6* alone does not simply explain *vir-1* autoimmunity gene expression phenotypes.

A group of flowering time genes paralleled the expression of immune response genes. The floral pathway integrator, *FT,* (Kinoshita & Richter, 2020) is upregulated in *vir-1* at 17°C but not 27°C (Supplementary Table 8). In addition, the expression of a group of genes known to function downstream of *FT* in floral development, including *FUL, SOC1*, *SEP3*, *SPL4*, *SPL5, AGL19* and *AGL24* phenocopied defence gene expression patterns (Supplementary Table 8, Supplementary Figures 3F-M).

In summary, diverse genes attributed to the different ETI and PTI layers of Arabidopsis innate immunity were upregulated in *vir-1* mutants at 17°C but not 27°C, together with mRNA encoding the SARD1 master defence transcription factor that controls SA-dependent and SA-independent defence responses.

vir-1 mutants exhibit temperature-sensitive pathogen resistance and localised cell death

A characteristic of autoimmunity is that plants show enhanced resistance to pathogens because defence gene expression is already upregulated prior to infection. We, therefore, asked whether the global changes in gene expression detected in *vir-1* resulted in a functional impact on pathogen infection. We examined the susceptibility of WT Col-0, *vir-1* and *fls2* (*flagellin sensing 2*) mutants to the biotrophic pathogenic bacterium *Pseudomonas syringae* pv. tomato (*Pto*) DC3000. The *fls2c* mutant allele (Zipfel *et al*, 2004) lacks the receptor for bacterial flagellin and is susceptible to infection, so is a positive control for infection in these experiments. We flooded seedlings grown at 17°C, 21°C and 27°C with *P. syringae* pv. tomato (*Pst)* DC3000. We found that *fls2c* mutants were more susceptible than Col-0 to infection at all temperatures, consistent with previous reports (Zipfel *et al*, 2004) (Figure 4A, Supplementary Figure 4, Supplementary Table 9). In contrast, *vir-1* mutants were more resistant to infection than Col-0 when grown at 17°C and 21°C, but there was no significant difference in infection levels between Col-0 and *vir-1* plants grown at 27°C. Therefore, the temperature-sensitive patterns of defence gene expression detected in *vir-1* convert to a corresponding change in immunity.

Localised premature cell death is a phenotype of plant immune responses to infection, and leaf lesions are a feature of some autoimmune genotypes (van Wersch *et al*, 2016; Freh *et al*, 2022). To investigate whether *vir-1* mutants exhibited elevated levels of cell death compared to WT Col-0 in the absence of pathogen infection, we stained seedlings grown in sterile conditions with the vitality marker trypan blue (TB). We recorded microscopy images and quantified the levels of detectable TB staining for 10 individual leaves of each genotype grown in each condition using ImageJ (Schneider *et al*, 2012). We detected the highest levels of cell death in *vir-1* grown at 17°C (Figure 4B and 4C, Supplementary Table 10). However, at 27°C, cell death patterns in *vir-1* were at negligible levels, comparable to those detected in WT Col-0 at 17°C and 27°C. We, therefore, conclude that *vir-1* mutants show elevated levels of premature cell death at 17°C when immune response pathways are autoactivated.

Overall, *vir-1* mutants' temperature-sensitive response to two orthogonal analyses of autoimmunity - enhanced pathogen resistance and increased premature cell death - is consistent with the global patterns of gene expression changes we detect at the RNA level. These findings suggest that the mRNA m^{6}A writer complex is required to dampen defence pathway signalling to prevent autoimmunity in the absence of pathogens but not for the defence responses that suppress *P. syringae* pv. tomato (*Pto*) DC3000 infection. We, therefore, conclude that *vir-1* mutants have a temperature-sensitive autoimmune phenotype.

mRNA m^{6}A levels in *vir-1* mutants are not temperature-sensitive

An ethyl methanesulfonate-induced 5' splice site mutation in intron 5 (G+1 to A) causes the *vir-1* allele, resulting in cryptic splicing events within exon 5 that disrupt the *VIR* open reading frame (Růžička *et al*, 2017). Since mutations that disrupt splice sites can be temperature-sensitive (Sablowski & Meyerowitz, 1998), we asked if the expression of *VIR* mRNA was restored at 27°C. However, we found no evidence from our RNA-seq data to support this idea (Supplementary 5A and 5B). We next asked whether mRNA m^{6}A levels in *vir-1* mutants were restored to wild-type levels at 27°C. We first used liquid chromatography-tandem mass spectrometry (LC-MS/MS) to analyse the m^{6}A/A (adenosine) ratio in poly(A)+ RNA purified from Col-0 and *vir-1* grown at 17°C and 27°C. The level of poly(A)+ RNA m^{6}A modification in the hypomorphic *vir-1* allele was reduced to approximately 10% of that detected in Col-0 at both 17°C and 27°C (Figure 5A, Supplementary Table 11), consistent with previous reports of reduced m^{6}A levels in *vir-1* mutants (Růžička *et al*, 2017; Parker *et al*, 2020). In addition to LC-MS/MS, we used the ONT DRS data to examine mRNA m^{6}A levels. We have previously mapped m^{6}A in ONT DRS data using the Differr and Yanocomp programs, which depend upon comparing WT and mutant genotypes (Parker *et al*, 2020, 2021a). We supplemented

Yanocomp analysis with m6Anet, a neural-network-based method that can call read-level m^6A stoichiometry without genotype comparison (Hendra *et al*, 2022). We found no restoration of m^6A levels identified by m6Anet (Figure 5B) or Yanocomp analysis (Supplementary Figure 5C) in *vir-1* at 27°C compared to 17°C. We conclude that the suppression of immune gene expression detected in *vir-1* at 27°C is not explained by an accompanying change in mRNA m^6A modification.

The visible developmental defects of *vir-1* mutants are separable from autoimmune gene expression

Arabidopsis autoimmune mutants characteristically show developmental defects that can be rescued by growth at elevated temperatures (Alcázar & Parker, 2011). We asked whether the impact of autoimmunity might explain the developmental phenotypes of *vir-1*. We examined the development of Col-0 and *vir-1* mutant plants from germination to flowering and seed-set at 17°C and 27°C. We included *acd6-1* as a positive control for an autoimmune mutant compromised in development at 17°C, which appears more like WT Col-0 when grown at 27°C. We found that the short stature and lack of apical dominance characterising the visible developmental phenotypes of *vir-1* mutants were not rescued by growth at 27°C (Figure 6A). However, we could replicate the previously reported developmental rescue of *acd6-1* mutants at 27°C compared to 17°C (Supplementary Figure 6A). We, therefore, conclude that the impact that loss of the mRNA m^6A writer complex has on development and defence gene expression programmes is separable.

Next, we asked if we could detect gene expression changes that might underpin developmental change in *vir-1* mutants. We identified significant gene expression differences consistently affected by the *vir-1* mutation across all our datasets, irrespective of temperature (adj.p < 0.001, log2FC>2.0) (Supplementary Table 12). The flowering time control gene, *FLC*, was the only gene significantly downregulated across all our *vir-1* experimental conditions. Only 58 genes were consistently upregulated. However, the most enriched GO term biological processes for these genes were “defence response”, “systemic acquired resistance”, and “defence response to other organism” (Supplementary Figure 6B, Supplementary Table 13), indicating that defence gene upregulation remains an important *vir-1* gene expression phenotype. For example, RNA encoding the flavin-dependent monooxygenase, FMO1, was upregulated in *vir-1* relative to WT Col-0 in all tested conditions (Supplementary Figure 6C). FMO1 is a critical regulator of systemic acquired resistance to pathogen infection (Hartmann *et al*, 2018). We also identified consistent upregulation of the AtNUDT24 nudix hydrolase. AtNUDT24 is uncharacterised, but other members of this protein family function to modify

signalling nucleotides in plant defence (Yu *et al*, 2022; Bartsch *et al*, 2006) or in RNA decapping and hydrolysis, among other roles (Laudenbach *et al*, 2021; Carreras-Puigvert *et al*, 2017).

Overall, we conclude that although defence gene activation in *vir-1* mutants is suppressed at 27°C, visible developmental defects are not, and autoimmune gene expression programmes remain a component of the *vir-1* mutant phenotype.

Altered poly(A) tail length distributions are a temperature-sensitive phenotype of *vir-1* mutants

To understand how the loss of mRNA m^{6}A might trigger an autoimmune response, we next asked if RNA processing was affected in *vir-1* mutants grown at different temperatures. Consistent with our previous reports (Parker *et al*, 2020, 2022), we found that genetic disruption of the mRNA m^{6}A writer complex resulted in a global shift to proximal poly(A) site usage in diverse mRNAs (Figure 7A). The scale of this effect was similar in *vir-1* mutants grown at 17°C and 27°C. Altered 3' end formation may trigger autoimmunity, but the subsequent signalling might be suppressed at 27°C, so we addressed this question differently. If alternative poly(A) site usage triggered the autoimmune response, it might be mediated by the CPSF30-YTH m^{6}A reader. We examined gene expression changes in *cpsf30-yth* mutants using ONT DRS. The *cpsf30-yth* mutants express a truncated protein comprising the N-terminal Zinc-Finger domains that bind the AAUAAA poly(A) signal, but lack the C-terminal YTH domain. We found *PR1* is not upregulated in *cpsf30-yth*, although it is upregulated in *fip37-4* mutants analysed alongside here as a positive control (Figure 7B). Therefore, this combination of data does not provide evidence that altered poly(A) site usage triggers the autoimmunity phenotypes of Arabidopsis mRNA m^{6}A writer complex mutants.

The cytoplasmic YTH reader domain proteins likely mediate specific impacts of m^{6}A on RNA fate (Brodersen & Arribas-Hernández, 2024). The most abundant of these are ECT2, 3 and 4 (Arribas-Hernández *et al*, 2018). We analysed a triple mutant in each gene, *te234* (Flores-Téllez *et al*, 2023) using ONT DRS. We found no evidence that *PR1* was upregulated in *te234.* In contrast, *PR1* upregulation was again detected in *fip37-4* mutants included here as a positive control (Figure 7C).

Finally, we asked if poly(A) tail length was altered in *vir-1* mutants. We have previously reported a change in poly(A) tail length profiles at specific genes in *vir-1* (Parker *et al*, 2020), and we asked if this was a more widespread phenotype. We used the ONT software Dorado to estimate transcript poly(A) tail length in our ONT DRS data. This analysis reveals a characteristic periodicity in estimated lengths of read poly(A) tails that likely reflects the

footprint of binding of multiple poly(A) binding proteins (PABPs) (Baer & Kornberg, 1983; Passmore & Coller, 2022). We found that the distribution of estimated poly(A) tail lengths was markedly different in *vir-1* compared to WT Col-0 - at 17°C; relatively fewer transcripts with short poly(A) tails and more with longer poly(A) tails are detected in *vir-1* compared to WT-Col-0 (Figure 7D). At 27°C, *vir-1* mutant mRNA poly(A) tail length profiles are different again, with a distribution more enriched in short poly(A) tails compared to WT Col-0 (Figure 7D). In contrast, the 30 nt poly(A) tail of *Saccharomyces cerevisiae ENOLASE II* RNA, used here as a spike-in calibration standard during ONT DRS library preparation, is consistent across all samples, with an estimated median tail length of 33 nt (Supplementary Figure 7A).

Changes in the global distributions of poly(A) tail length may be partly due to differences in the sets of genes expressed at detectable levels in the different conditions. To examine the differences in tail length per gene and exclude genes that were only expressed in single conditions, we used the Wasserstein distance metric to quantify shifts in mean per gene tail length distributions between conditions (Parker *et al*, 2021b). This analysis identified a shift towards longer mean poly(A) tails in *vir-1* at 17°C compared to Col-0 and a shift towards shorter mean poly(A) tails in *vir-1* at 27°C, consistent with the different distributions of estimated poly(A) tails lengths (Figure 7E, Supplementary Table 14). Temperature-sensitive changes in mean poly(A) tail length in Col-0 were modest by comparison (Figure 7F). We asked if the shift in mean poly(A) tail length was directly associated with the loss of m^6A modification. We found that while genes with m6Anet-predicted m^6A sites had shorter poly(A) tails, the temperature-dependent differences in poly(A) tail length distribution were seen in genes predicted to be either m^6A-modified or non-modified (Supplementary Figure 7B).

In summary, our findings reveal global changes in poly(A) tail length distributions as the primary temperature-sensitive mRNA processing phenotype of *vir-1* mutants. This global phenotype is not restricted to genes that function in defence responses or to those transcripts predicted to have lost m^6A modification.

DISCUSSION

We have discovered that disruption of the mRNA m^{6}A modification complex triggers autoimmunity in Arabidopsis. Using a combination of Illumina RNA-seq and ONT DRS, we reveal, in unprecedented detail, the temperature-sensitive changes in RNA expression, modification and processing caused by mRNA m^{6}A writer complex depletion. At 17°C, most gene expression class changes in *vir-1* mRNA m^{6}A writer complex mutants are explained by defence gene activation. By exploiting the established temperature sensitivity of Arabidopsis immunity, we found that the vast majority of these gene expression changes did not occur when we grew the *vir-1* mRNA m^{6}A writer mutant at 27°C. We used orthogonal experimental approaches to examine the biological impact of this defence gene activation. We found temperature-sensitive enhanced levels of premature cell death and resistance to *P. syringae* Pst D3000 pathogen infection in *vir-1* mutants consistent with the idea that these gene expression changes convert into functional consequences for immunity. Not all gene expression changes, or all developmental phenotypes of *vir-1* mutants, were rescued by elevated temperature, demonstrating that the impacts of m^{6}A-dependent changes on gene expression are separable. Together, these different lines of evidence all point to the disruption of the mRNA m^{6}A writer complex triggering autoimmunity in Arabidopsis.

The autoimmune phenotypes of Arabidopsis m^{6}A writer complex mutants have not previously been described. However, while analysing the impact of mRNA m^{6}A on plant pathogen infection, it was recently reported that Arabidopsis mutants defective in METTL3, VIR and WTAP orthologs, and a line ectopically overexpressing the mRNA m^{6}A demethylase ALKBH10B, were all more resistant to infection by *P. syringae* DC3000, *P. syringae pv maculicola* and a fungal pathogen *Botrytis cinerea* (Prall *et al*, 2023). Consistent with this, genes commonly upregulated in METTL3 ortholog mutant and ectopic ALKBH10B expression lines are enriched in GO term annotations for defence signalling (Prall *et al*, 2023). Furthermore, early microarray analysis of METTL3 ortholog mutants reported a general enrichment among the overexpressed genes for GO terms related to stress responses (Bodi *et al*, 2012). These independent findings are consistent with our analysis of *fip37-4* and *vir-1* and generalise the idea that autoimmunity is a major Arabidopsis mRNA m^{6}A writer complex mutant phenotype.

These discoveries raise the key question of how disruption of mRNA m^{6}A writer complexes triggers autoimmunity. Our analysis does not explain how defence pathways are autoactivated in Arabidopsis mRNA m^{6}A writer complex mutants. Remarkably, given its importance, the mechanism by which modified RNAs ablate TLR signalling in humans is also

unknown. We first considered whether m^{6}A readers might mediate the autoactivation of defence gene expression. However, we found no evidence that either *cpsf30-yth* mutants or *te234* mutants phenocopied the defence gene expression of *vir-1* mutants. There are 13 m^{6}A-reading YTH domain-containing proteins encoded in the Arabidopsis genome. Therefore, approaches that resolve redundancy in their function (Flores-Téllez *et al*, 2023) will be required to test an association with autoimmunity further. The major temperature-sensitive RNA phenotype we detected in *vir-1* mutants was a global change in mRNA poly(A) tail length: we found relatively fewer RNAs with short poly(A) tails (<40 nt) and relatively more with longer poly(A) tails (>100nt) compared to WT Col-0 at 17°C but this phenotype was reversed at 27°C. This finding could indicate that the trimming of longer poly(A) tails - an essential feature of newly transcribed mRNAs (Passmore & Coller, 2022) - is defective and/or mRNAs with short poly(A) tails are more susceptible to decay in *vir-1* mutants at 17°C. Poly(A) tails can reduce innate immune responses of human cells to RNA (Koski *et al*, 2004). Furthermore, autoimmunity and pleiotropic developmental defects are phenotypes of Arabidopsis mutants defective in the nuclear poly(A) polymerase, PAP1, that catalyses mRNA poly(A) tail formation (Vi *et al*, 2013). However, the inter-relatedness of the phenotypes we detect here is not yet clear. Poly(A) tail length changes were not restricted to transcripts with predicted m^{6}A sites, indicating this change is not a direct result of m^{6}A loss. Nor were poly(A) tail length changes restricted to transcripts involved in defence functions. Increased poly(A) tail length is a stress response phenotype of different species (Tudek *et al*, 2021; Yamagishi *et al*, 2024) and promotes stress granule formation in humans (Yamagishi *et al*, 2024; Tsai *et al*, 2025). Therefore, the temperature-sensitive poly(A) tail length changes we detect here may be a previously unappreciated autoimmunity phenotype. An aspect of RNA biology we have not explored is whether changes in condensate association caused by loss of mRNA m^{6}A might trigger autoimmunity. mRNA m^{6}A modifications can influence separation into biomolecular condensates such as human stress granules (Ries *et al*, 2023). Significantly, the buffering of self RNA by condensates regulates human innate immune responses (Maharana *et al*, 2022). Analysing other proteins more closely connected to Arabidopsis poly(A) tail processing and RNA fate (Sasse *et al*, 2024) could help unravel connections between RNA modification, poly(A) tail length, altered RNA homeostasis and the causes or consequences of autoimmunity.

Different receptors detect RNA as a molecular signature of pathogen infection in humans, and RNA's availability, localisation, and structure (including sequence and modification) are essential criteria for distinguishing self and non-self (Schlee & Hartmann, 2016; Bartok & Hartmann, 2020). For example, uridine mononucleotides and di or

trinucleotides are bound on different sites of TLR8 in monocyte endosomes in a manner that depends on upstream RNAse 2 and T2 processing of pathogen RNA (Ostendorf *et al*, 2020). RNAs purified from *P. syringae* DC3000 bacteria or transcribed *in vitro* and infiltrated into Arabidopsis leaves activate innate immunity, demonstrating that non-self RNAs can trigger immune responses in Arabidopsis (Lee *et al*, 2016). Aside from the RNAi machinery, which plays crucial roles in viral defence in plants (Lopez-Gomollon & Baulcombe, 2022), receptors that recognise pathogen RNAs are poorly characterised in plants. However, plant TIR domains have recently been found to hydrolyse RNA (Yu *et al*, 2022). Compared to DNA, RNA is the preferred substrate for TIR domains to synthesise 2',3',-cAMP/cGMP molecules that signal cell death in the hypersensitive response (Yu *et al*, 2022). Crucially, a mutation that disrupts this synthetase activity is sufficient to block cell death signalling (Yu *et al*, 2022). TIR domains are frequently found in Arabidopsis NLR proteins and can also be expressed as TIR-only proteins (Essuman *et al*, 2022) encoded by TIR-only genes or the widespread prematurely terminated transcripts of NLR genes (Parker *et al*, 2021b). We found that mRNAs encoding TIR domain proteins, including TX0, for which RNA hydrolysing activity has been demonstrated (Yu *et al*, 2022), were significantly upregulated in *vir-1* mutants. The natural RNA substrates of Arabidopsis TIR domains are unknown. An important question is whether TIR domains sense non-self RNAs or perturbed RNA homeostasis that indicates pathogen activity. The nudix hydrolase family member NUDT7 acts as a phosphodiesterase to modify 2'3'-cAMP/cGMP and thus modulates signalling through EDS1 (Yu *et al*, 2022). Notably, one of the most consistently upregulated genes in *vir-1* is the uncharacterised nudix hydrolase, AtNUDT24.

It may not be the loss of mRNA m^6A itself that triggers autoimmunity. ETI functions to detect pathogen activity that disrupts host cell proteins or processes and activates an immune response. In this way, NLRs act as guards, with the effector-targeted host cell proteins or processes being guardees (Dangl & Jones, 2001; Van der Biezen & Jones, 1998; Remick *et al*, 2023). It is possible that the mRNA m^6A writer complex is a guardee and that disruption of the writer complex, rather than the absence of mRNA m^6A, is detected and triggers autoimmune signalling. Therefore, defence signalling pathways in *vir-1* mutants may directly detect non-modified RNA, a disrupted mRNA m^6A writer complex, poly(A) tail perturbation, or changed RNA homeostasis resulting from decay or condensate association. However, the connection between disrupted m^6A writer complex and autoimmunity may be even more indirect. Loss of m^6A is associated with diverse changes in gene expression and pleiotropic developmental changes. Therefore, if the changes in gene expression, RNA processing, or development found in mRNA m^6A writer complex mutants phenocopy features of pathogen

infection, they may indirectly trigger immune pathway activation. Consequently, understanding how immune gene expression is activated is crucial to understanding the directness by which mRNA m^6A impacts these diverse RNA and developmental phenotypes.

Our findings, therefore, have practical implications for studying the impact of mRNA m^6A on plant biology. Since most gene expression changes in mRNA m^6A writer complex mutants at lower ambient temperatures are caused by autoactivation of defence gene expression, the interpretation of the effects of mRNA m^6A will be complicated by indirect changes that vary according to environmental conditions (such as temperature), which may differ between studies. Mutating defence signalling hubs in mRNA m^6A writer complex mutant backgrounds might suppress autoimmunity but not necessarily comprehensively block autoimmune signalling. Our global transcriptome analysis only provides snapshots of gene expression changes in Arabidopsis seedlings. However, understanding how mRNA m^6A directly influences mRNA processing and fate and, hence, development and autoimmunity will require alternative experimental approaches. Determining immediate gene expression changes following mRNA m^6A writer complex shutdown using, for example, proteolysis targeting chimaeras (PROTACS) (Békés *et al*, 2022) in defined cell types and developmental contexts may help us understand the direct roles of mRNA m^6A.

In conclusion, our study establishes a new conceptual framework for analysing the impact of mRNA m^6A on plant biology. The molecular basis of the events that trigger mRNA m^6A writer complex-dependent autoimmunity is unknown, but uncovering this should lead to fundamental insights into the role of mRNA m^6A in plant biology and how defence gene signalling occurs.

MATERIALS and METHODS

Plant Material

Wild-type *Arabidopsis thaliana* accession Col-0 and *te234* (Arribas-Hernández *et al*, 2020) were obtained from the Nottingham Arabidopsis Stock Centre. The *vir-1* and VIR-complemented (VIR::GFP-VIR) lines (Růžička *et al*, 2017) were from K. Růžička, Brno, Czechia; *acd6-1* was from J. Greenberg, Chicago, USA; *fip37-4* was from R. Fray, Nottingham, UK; *fls2c* (SAIL_691C4) (Zipfel *et al*, 2004) was from P. Hemsley, Dundee, UK; *cpsf30-yth* (GK477H04) was from Ł. Szewc, Poznań, Poland.

Plant Growth Conditions

Seeds were sown on MS10 medium plates, stratified at 4°C for 2 days, germinated in a controlled environment at 22°C under 16 hr light/8 hr dark conditions and harvested for RNA purification 14 days after transfer to 22°C. For temperature assays, plant growth chambers were set to either 17°C or 27 °C, with all other conditions the same as above. Seedlings were harvested 14 days after germination during the first two hours of the light period following an 8-hour dark phase. Four-week-old plants were used for phenotyping the adult plants at 17°C or 27 °C.

Trypan Blue Staining

Trypan blue staining was performed on leaves from 4-week-old plants of WT Col-0 and *vir-1* grown at 17°C and 27°C. Leaves were stained in a solution of Tris-EDTA equilibrated phenol (pH 8) (25%), glycerol (25% v/v), lactic acid (25% v/v) with trypan blue (10mg/ml). Leaves were treated with staining solution for 10 minutes at 95°C then incubated overnight at room temperature. Leaves were destained in chloral hydrate solution twice, for 4 h and overnight. Stained leaves were imaged under a Zeiss histology microscope at 10x magnification. Images were imported into ImageJ (Schneider *et al*, 2012), and the total stained area was measured in pixels, with the stained area expressed as a percentage of the total leaf area. Data collected from 10 leaves per condition was plotted, and a two-way ANOVA test with post hoc Turkey's HSD tests was used to assess the effects of genotype and temperature and their interaction on the percentage of leaf stained.

Genotyping of Arabidopsis

Individual mutants and progeny from crosses were genotyped by PCR analysis of purified DNA using a combination of derived cleaved amplified polymorphic sequence (dCAPS)

markers (Michaels & Amasino, 1998), T-DNA insertion markers and sequencing. Genotyping primer pairs used in the study are listed in Supplementary Table 15.

Pathogenesis Assays

Arabidopsis Col-0, *vir-1* and *fls2c* seedlings were treated with *Pseudomonas syringae* pv tomato (Pto) DC3000 using flood inoculation. Bacteria were cultured on MG agar supplemented with rifampicin at 28°C for 24-48 h. Four-week-old seedlings flood-inoculated with a bacterial suspension of *P. syringae* DC3000 ($5x10^6$ Colony-Forming Units (CFU)/ml) containing 0.025% Silwet L-77. Sterilised seedlings were grown on half-strength MS agar for 2-3 weeks at 17°C, 21°C and 27°C before inoculation. The bacterial suspension was applied to the Arabidopsis seedlings, and plates were incubated at room temperature for 2-3 minutes. Excess liquid was drained, and seedlings were maintained at growing temperatures for three days. Bacterial growth was calculated using serial dilution of material from three seedlings per plate and recorded as CFU/mg. The significance of changes in bacterial growth in the differing conditions was tested using ANOVA. The experiment was repeated to confirm results.

RNA Isolation

Total RNA was isolated using the RNeasy Plant Mini kit (Qiagen) and treated with RNAse-free DNase (Promega-M6101). RNA concentration and integrity were measured using a NanoDrop one spectrophotometer and Agilent 4150 Tapestation.

Gene expression analysis by RT-qPCR

Total RNA was extracted from 14-day-old seedlings. Total RNAs were treated with RNAse-free DNase (Promega-M6101). First-strand cDNAs were synthesised using SuperScript™ III Reverse Transcriptase (Thermo Fisher Scientific-12574026). qPCR was carried out on a LightCycler® 96 Instrument using Brilliant III Ultra-Fast SYBR Green qRT-PCR Master Mix (Agilent-600886). Three biological replicates (independently harvested samples) with three technical replicates for each were analysed. Relative expression levels were determined using the $2^{-\Delta\Delta CT}$ method. Arabidopsis *UBQ10* (AT4G05320) was used as internal control. qPCR primer pairs are listed in Supplementary Table 15.

Preparation of libraries for Illumina RNA-sequencing

Illumina RNA-seq libraries were prepared by Genewiz (Azenta LifeScience) using NEB Next Ultra Directional Library Prep Kit according to the manufacturer's instructions. Paired-end sequencing with a read length of 150bp was carried out on the Illumina NovaSeq X following

the manufacturer's instructions. Raw sequence data was converted to fastq and de-multiplexed using Illumina bcl2fastq version 2.20.

Processing of Illumina RNA-seq data and differential gene expression analysis

Quality assessment of RNA-seq reads was performed using FastQC (Andrews, 2017). For digital expression, the Salmon index was built using Arabidopsis Araport11 transcript annotations (Cheng *et al*, 2017). Transcript and gene-level counts were estimated using Salmon (with gtf option and Araport 11 annotation) (version 1.9.0) (Krishnakumar *et al*, 2015). Differential expression analysis was performed in edgeR (version 4.2.2) using a quasi-likelihood generalised linear model (glmQLFit). Annotation of genes of interest, categorising them as defence, flowering or other and returning GO annotation with further annotation was performed using custom scripts: https://github.com/bartongroup/PT_Arabidopsis_names_to_annot. To visualise dimensional reduction in the context of RNA-seq quality control, PCA plots were created using ggplot2 (version 3.5.1). Correlation and heatmap plots were generated with the ptr script from the Trinity RNAseq package (version 2.15.2) (Grabherr *et al*, 2011). GO enrichment heatmap were made using msbio (metascape)(v3.5.20240901) (Zhou *et al*, 2019).

Functional enrichment analysis was performed using a combination of Goseq (version 1.42.0) (Young *et al*, 2010) and g:Profiler (version e111_eg58_p18_f463989d) with the g:SCS multiple testing correction method and a significance threshold < 0.05 (Kolberg *et al*, 2023). Domain enrichment analysis was performed in DAVID (Sherman *et al*, 2022) using a FDR significance threshold of < 0.05.

To determine whether pathogen contamination was present in the *vir-1* RNA-seq samples, reads were mapped to the TAIR10 genome, and from the resulting bam file, unmapped reads were returned using STAR (version 2.7.11b) (Dobin *et al*, 2013). BBnorm (October 19, 2017) was then used to normalise the "unmapped" reads with the following setting "target=75 min=3" (Bushnell, 2022). The normalised reads were assembled using Trinity (Grabherr *et al*, 2011) (version 2.15.2) with –trimmomatic –no_normalise. The transcriptome assembly was processed using cd-hit-est (version 4.8.1) (-c 0.90 -n 8 -T 24 -M 0) (Fu *et al*, 2012a) to reduce redundancy at 90%. The resulting final transcriptome assembly was then searched against Genbank NR with Diamond-BLASTP using Diamond (version v2.0.5.143) (Buchfink *et al*, 2021). The diamond BLASTP output was post-taxonomically annotated using https://github.com/peterthorpe5/public_scripts/tree/master/Diamond_BLAST_add_taxonomic_info. The final taxonomically assigned BLAST output was then interrogated for the presence

of plant pathogens, as defined here (https://phytopathdb.org/pathogens_eg/). Digital expression per condition to this assembly was estimated using Salmon (Patro *et al*, 2017), and differential expression analysis was performed as described above.

ONT DRS Library Preparation

Total RNA was isolated, as detailed above. Poly(A)+ RNA was purified from approximately 100μg of total RNA using the Dynabeads mRNA purification kit (Thermo Fisher Scientific) following the manufacturer's instructions. The quality and quantity of mRNA were assessed using the Nanodrop one spectrophotometer (Thermo Fisher Scientific) and Tape station 4150 (Agilent Technologies). ONT DRS libraries were prepared from 100ng poly(A)+ RNA for the WT Col-0 - *vir-1* comparison at 17°C and 27°C. All other ONT DRS libraries were prepared from 500ng poly(A)+ RNA. Libraries were made using the Direct RNA sequencing kit (SQK-RNA002; Oxford Nanopore Technologies) according to the manufacturer's instructions. The poly(T) adapter was ligated to the mRNA using T4 DNA ligase (New England Biolabs) in the Quick Ligase reaction buffer (New England Biolabs) for 15 min at room temperature. First-strand cDNA was synthesised by SuperScript III Reverse Transcriptase (Thermo Fisher Scientific) using the oligo(dT) adapter. The RNA–cDNA hybrid was then purified using Agencourt RNAClean XP magnetic beads (Beckman Coulter). The sequencing adapter was ligated to the mRNA using T4 DNA ligase (New England Biolabs) in the Quick Ligase reaction buffer (New England Biolabs) for 15 min at room temperature followed by a second purification step using Agencourt beads (as described above). Libraries were loaded onto R9 version SpotON Flow Cells (Oxford Nanopore Technologies) and sequenced using a GridION device at the Tayside Centre for Genomic Analysis, School of Medicine, University of Dundee, for a 48-hour runtime. Four biological replicates were performed for each genotype.

ONT DRS mapping

Reads were basecalled using Dorado version 0.5.3 (Oxford Nanopore Technologies) using the rna002_70bps_hac@v3 high accuracy model. Reads were aligned to the Araport11 transcriptome (Cheng *et al*, 2017) and the TAIR10 Arabidopsis genome (Lamesch *et al*, 2012) using minimap2 version 2.17 (Li, 2018) configured for spliced alignment. The following parameters were used for both alignments: --end-seed-pen=15 for end seed penalties, -A1, -B1, -O2,32, -E1,0 and -C9 to tune alignment scoring. For genomic alignment, splice junction information was incorporated using the --junc-bed parameter, which referenced the annotated introns BED file. A junction bonus of 10 (--junc-bonus=10) was applied to prioritise alignments that utilised known splice junctions, increasing alignment accuracy for spliced reads. The

spliced alignment was optimised with parameters -k14, -uf, -w5, --splice, and -g2000, along with a maximum intron size of 200,000 (-G200000), --splice-flank=yes for spliced alignment flanking detection, and -z200 for seeding thresholds. Alignments were converted to BAM files and indexed using samtools version 1.18.

Prediction of m^6A in ONT DRS data using m6Anet

Event information was extracted from raw signal data and transcriptome alignments using the f5c implementation of eventalign with event scaling (Gamaarachchi *et al*, 2020). Aligned event files were processed using m6anet (Hendra *et al*, 2022). Data preparation and inference was performed using the pretrained Arabidopsis model with the default read probability threshold of <0.0033. Predicted sites of modification were filtered using the recommended probability-modified threshold of >0.9 (Hendra *et al*, 2022). The distribution of predicted modification ratios for all sites passing this threshold was plotted for each condition.

Analysis of poly(A) site usage in ONT DRS data

Differential 3' analysis was performed on bam files using the d3pendr tool as described previously (Parker *et al*, 2021b). The statistical significance of the 3' shift was assessed by permuting read alignments between the control and treatment distributions to determine the maximum distance achieved by random sampling.

Estimation of poly(A) tail length in ONT DRS data

The length of poly(A) tails per read was estimated using "--no-trim --estimate-poly-a" with the following model: rna002_70bps_hac@v3 in Dorado (version 0.5.3). Reads were mapped to the Araport 11 transcriptome using minimap2 (see above), and the resulting bam file was used to generate a read-to transcript table for further interrogation. Differences in mean poly(A) tail length per gene between conditions were calculated as previously described (Parker *et al*, 2020). In brief, poly(A) tail lengths were aggregated by gene ID, and where genes were present with at least ten reads in both conditions, the distributions of poly(A) tail lengths were compared using the Wasserstein distance. Significance was assessed using a permutation test with 999 bootstraps. Genes were classed as m^6A-modified if they had at least one site above the probability-modified threshold of >0.9 in at least one Col-0 sample.

Gene tracks

Gene track figures were generated using Matplotlib (version 3.9.2) from normalised bigwig files of Illumina RNA-Seq coverage and pooled bam files of reads per condition. For tracks

with >100 ONT DRS reads per condition, a random subsample of 100 reads per track was plotted.

m^6A liquid chromatography with tandem mass spectrometry

m^6A analysis using tandem liquid chromatography-mass spectroscopy (LC/MS-MS) was performed as previously described (Parker *et al*, 2020, 2021b). LC/MS-MS was carried out by the FingerPrints Proteomics facility at the University of Dundee. A two-way ANOVA test was used to assess the effects of genotype and temperature and their interaction on the ratio of m^6A to A.

Code and data availability

Illumina FASTQ and ONT FAST5 files for the 17ºC and 27ºC dataset are deposited in the ENA under accession code PRJEB85795. ONT FAST5 for the *te234* and *cpsf30-yth* datasets are deposited in the ENA under accession codes PRJEB85859 and PRJEB85860 respectively. Source data for LC-MS, flood inoculation and image staining are available in supporting files. Source code, R notebooks and Snakemake (Mölder *et al*, 2021) pipelines are available at github.com/bartongroup/m6a_arabidopsis_autoimmunity.

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Competing Interests

The authors declare no competing interests.

FIGURES

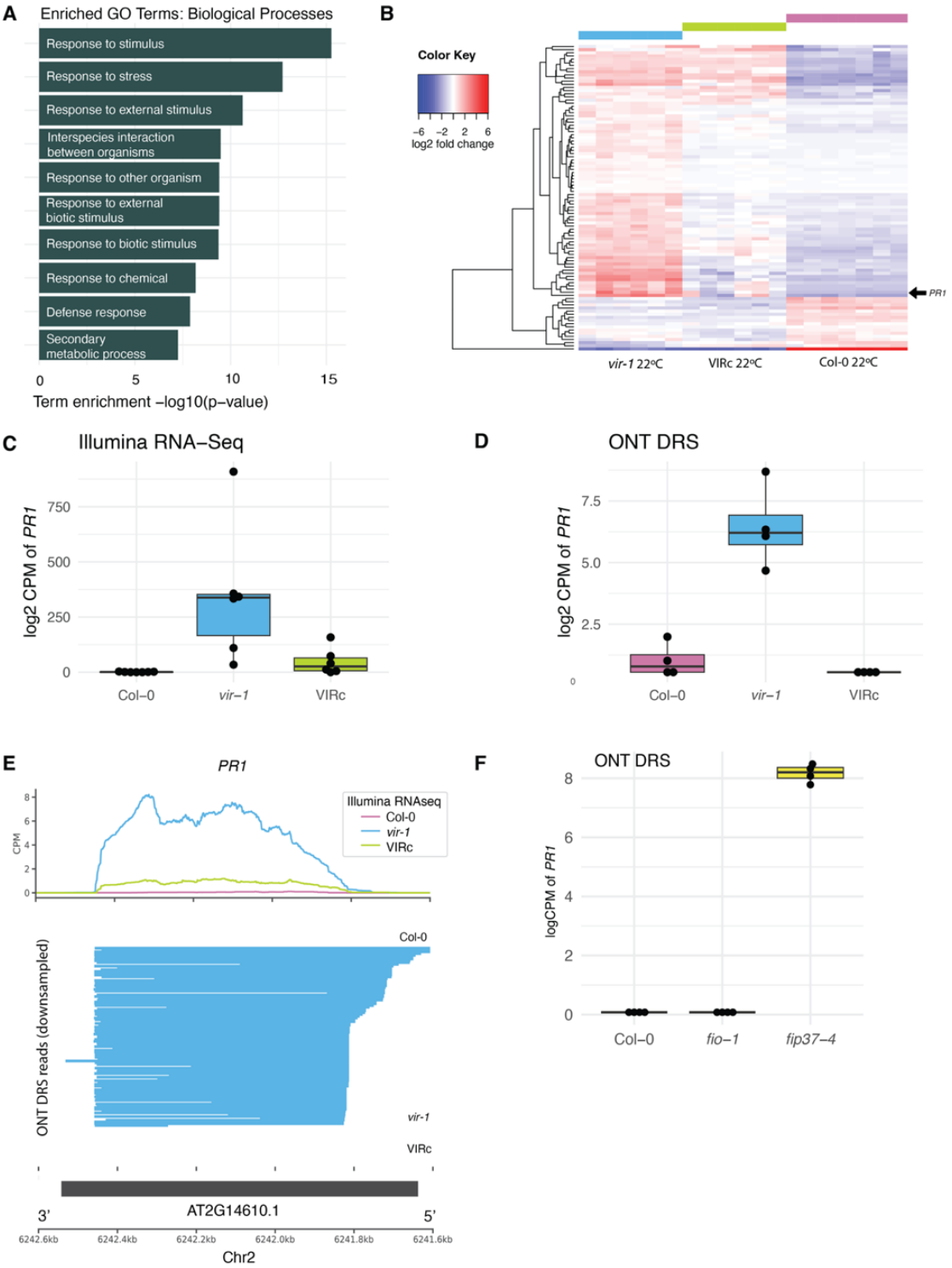


Figure 1: Immune gene expression is activated in m^{6}A writer complex mutants.

A) Top 10 gene ontology terms enriched in the set of 597 genes significantly upregulated (FDR < 0.001, log2FC > 2.0) in *vir-1* mutants compared to Col-0 WT at 20°C. B) Heatmap showing the TMM-FPKM normalised log2 centred fold expression between *vir-1*, Col-0 and VIRc for all genes with TAIR annotations including the term 'defense/defence'. *PR1* (AT2G14610) is highlighted with an arrow. C) Normalised log2 counts per million of *PR1* (AT2G14610) in Col-

0 (n = 7), *vir-1* (n = 6) and VIRc (n = 6) in Illumina RNA-seq. Boxes represent the interquartile range of the logged values. D) Normalised log2 counts per million of *PR1* (AT2G14610) in Col-0, Col-0, *vir-1* and VIRc in ONT DRS reads (n= 4 samples per genotype). E) Upregulation of *PR1* (AT2G14610) in *vir-1* at 20°C*,* shown by a gene track of Illumina RNA-seq and downsampled ONT DRS reads. C) Normalised log2 counts per million of *PR1* (AT2G14610) in Col-0, *fip37-4* and *fio-1* at 20°C in ONT DRS, showing the upregulation of *PR1* in *fip37-4*

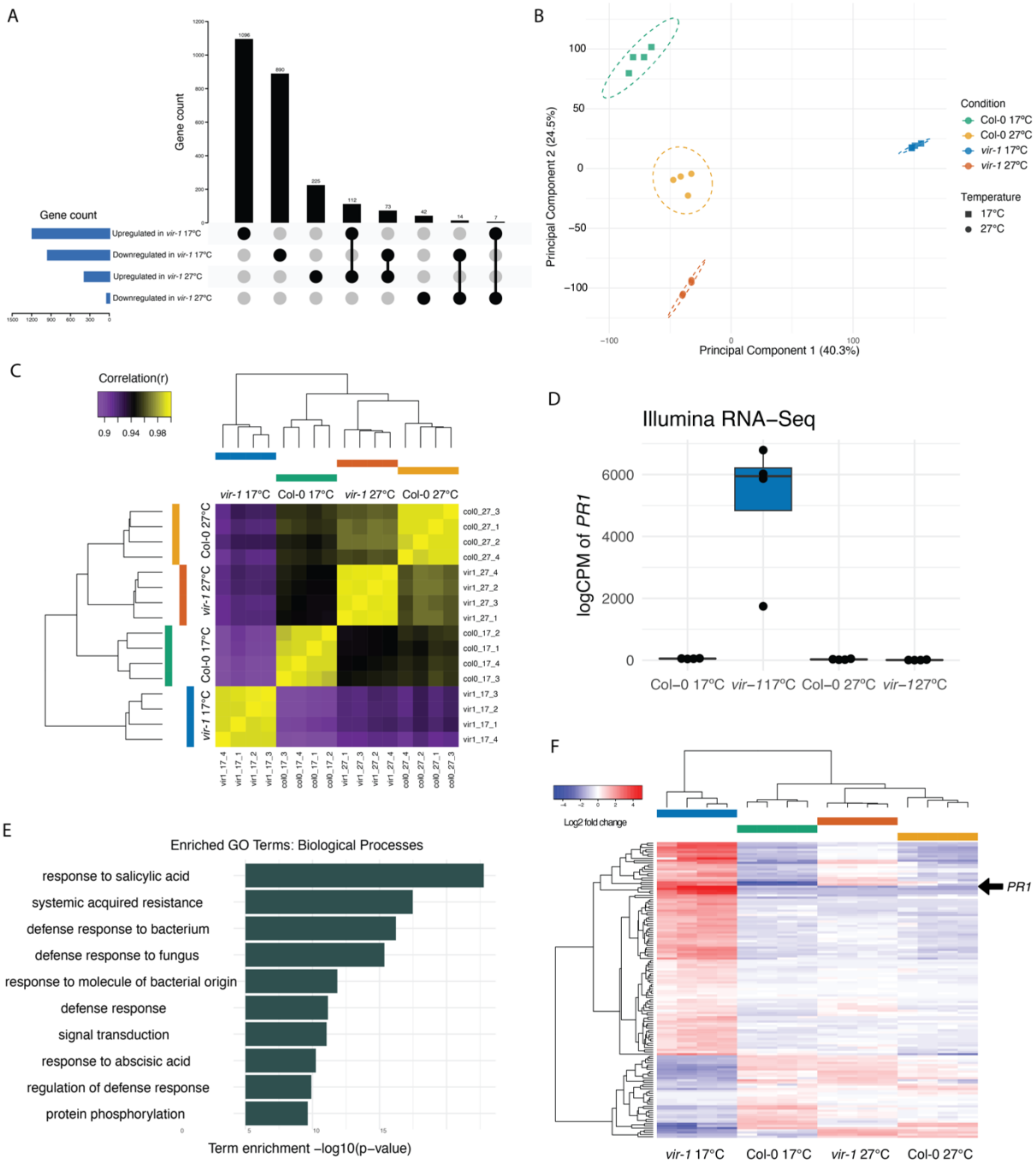


Figure 2: Loss of m^{6}A triggers a temperature-sensitive autoimmune response.

A) Upset plot showing the overlap in significantly upregulated and downregulated genes (log2FC +/- 2.0 FDR < 0.001) in *vir-1* at 17°C compared to Col-0 at 17°C and *vir-1* at 27°C compared to Col-0 at 27°C. B) Principal component analysis showing the clustering of samples by experimental condition (including genotype) and temperature. C) Correlation matrix and hierarchical clustering of expression profiles for each condition. The clustering shows that gene expression patterns are distinct for all conditions. In addition, biological replicates within conditions cluster together. However, the gene expression patterns detected in *vir-1* separate

as the most different of all possible comparisons. D) Significant upregulation of *PR1* (AT2G14610) in *vir-1* at 17°C*,* shown by a boxplot of normalised expression (log 2 counts per million) in Illumina RNA-seq data (n= 4 samples per genotype). E) Most enriched GO terms among genes significantly upregulated (FDR < 0.001, log2FC<2.0) in *vir-1* at 17°C compared to the average of: Col-0 17°C, 27°C and *vir-1* at 27°C. Source data available in Supplementary Table 6. F) Heatmap showing the TMM-FPMK normalised log2 centred fold change for all differentially regulated genes in *vir-1* at 17°C (log2FC +/- 2.0 FDR < 0.001) with TAIR annotations including 'defense/defence' for conditions *vir-1* at 17°C, 27°C, Col-0 at 17°C and 27°C. *PR1* (AT2G14610) is highlighted with an arrow.

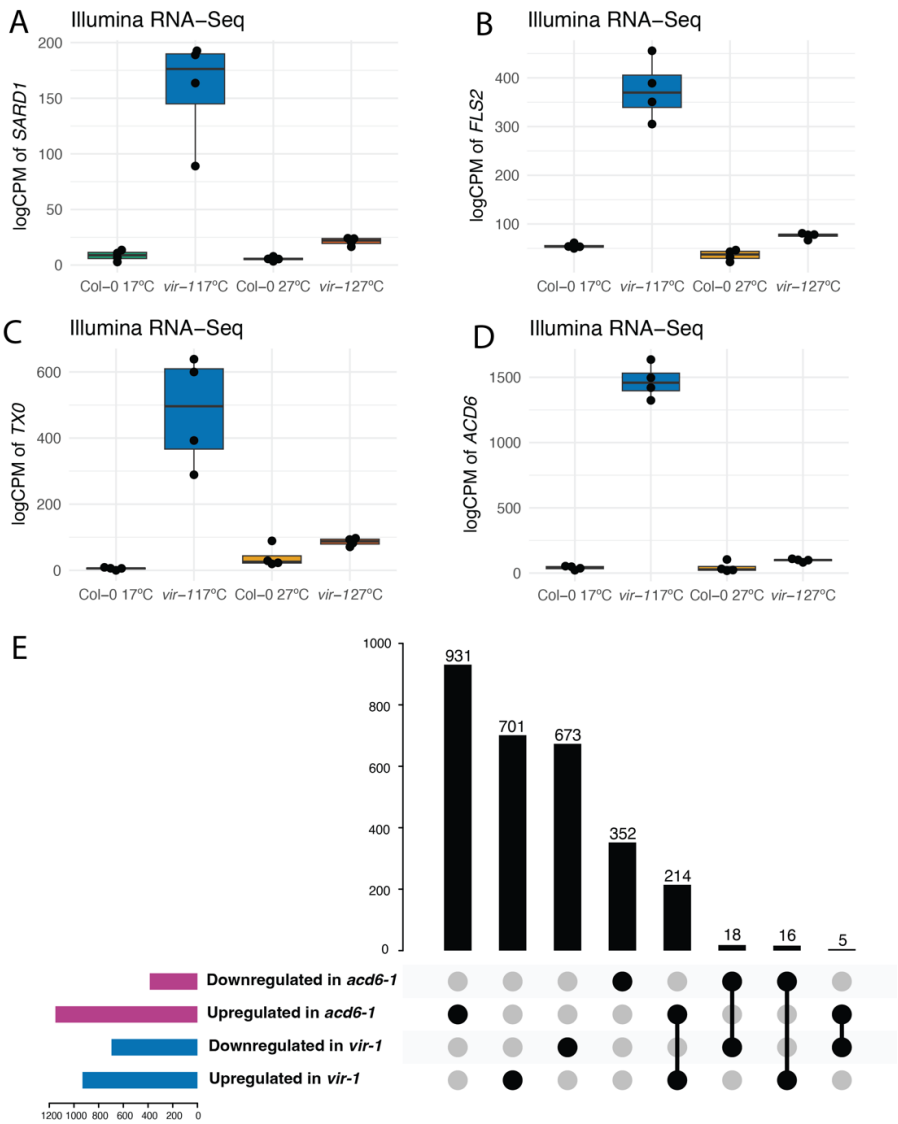


Figure 3: Defence genes that function in diverse aspects of immunity are upregulated in *vir-1* mutants

A) Significant upregulation of *SARD1* (AT1G73805) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log2 counts per million) in Illumina RNA-seq data (n = 4 samples per condition). B) Significant upregulation of *FLS2* (AT5G46330) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log2 counts per million) in Illumina RNA-seq data (n = 4 samples per condition). C) Significant upregulation of *TX0* (AT1G57630) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log2 counts per million) in Illumina RNA-seq data (n = 4 samples per condition). D) Significant upregulation of *ACD6* (AT4G14400) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log2 counts per million) in Illumina RNA-seq data (n = 4 samples per condition). E) Upset plot showing modest overlap in differentially upregulated genes between *vir-1* at 17°C and previously published *acd6-1* RNA-seq data (Fabian *et al*, 2023).

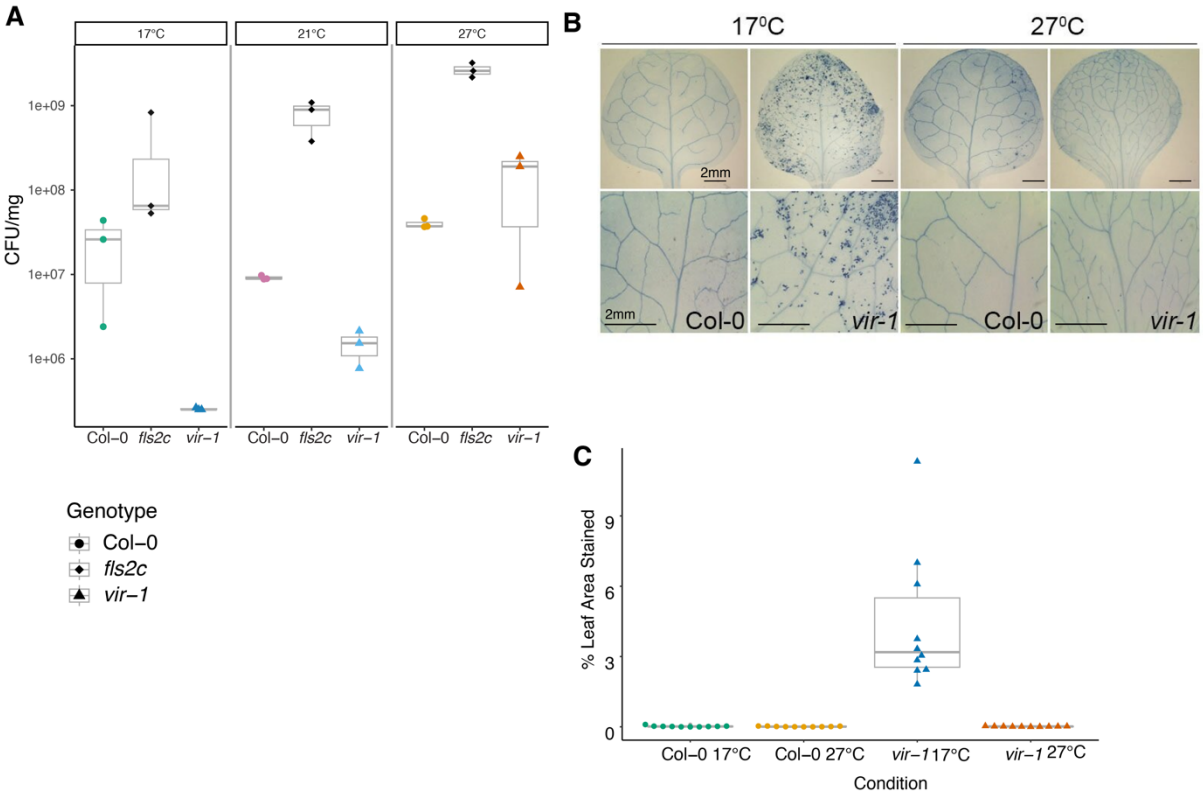


Figure 4: *vir-1* mutants exhibit temperature-sensitive pathogen resistance and localised cell death.

A) Four-week-old Col-0 WT, *vir-1* and *fls2c* seedlings flood-inoculated with a bacterial suspension of *Pst* DC3000 ($5x10^6$ CFU/ml) and 0.025% v/v Silwet L-77. Bacterial populations were quantified at 3 days post inoculation (dpi) (n = 3 per condition). One way ANOVA tests on each genotype revealed a significant effect of temperature in the *vir-1* genotype (F = 37.23, p = 0.0358) which was not present in Col-0 WT. Source data available in Supplementary Table 9. This experimental analysis was replicated independently in Supplementary Figure 4. B) Trypan blue staining of Col-0 WT and *vir-1* mutant leaves imaged with a Zeiss histology microscope at 10x magnification. C) Estimation of trypan blue staining patterns using ImageJ (n = 10 per condition). Two-way ANOVA revealed significant effects of temperature (F = 22.34, $p = 3.45 \times 10^{-5}$), genotype (F = 22.18, $p = 3.63 \times 10^{-5}$), and their interaction (F = 22.16, $p = 3.66 \times 10^{-5}$). Post hoc comparisons using Tukey's HSD test indicated that *vir-1* at 17°C significantly differed from all other conditions ($p < 0.0001$). Source data available in Supplementary Table 10.

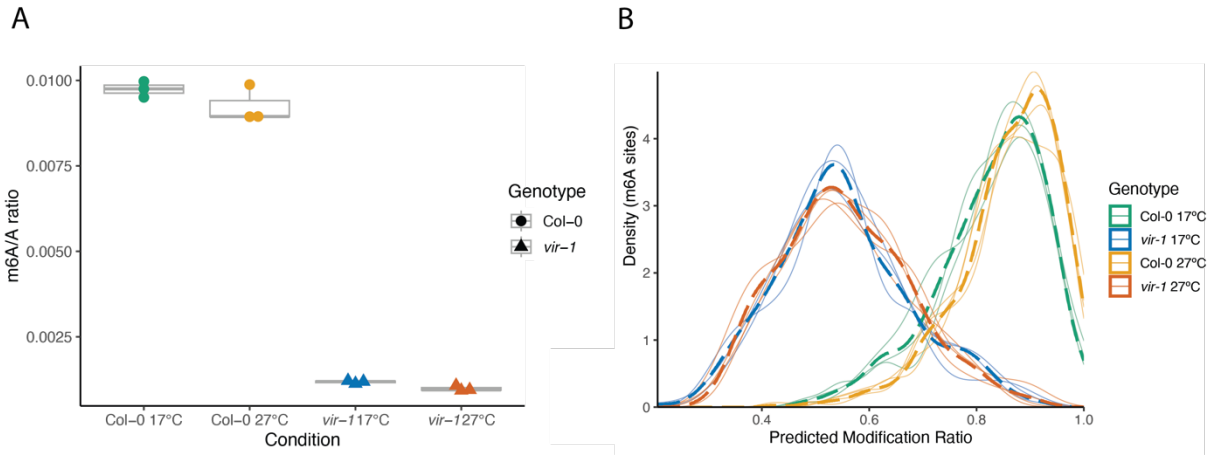


Figure 5: m^{6}A levels in *vir-1* mutants are not temperature-sensitive.

A) LC-MS/MS analysis showing the significant effect of genotype on the m^{6}A/A ratio and the lack of significant interaction between genotype and temperature on m^{6}A levels (two-way ANOVA; $p<0.001$) ($n = 3$ per condition). Source data available in Supplementary Table 11. B) Density distribution of the ratio of m^{6}A modification per site for all sites with probability modification > 0.9 predicted by m6Anet. Individual replicates are plotted as solid lines, with the combined density of a condition (genotype and temperature) plotted as a dashed line. 3545 sites were predicted to have an m^{6}A modified site in at least one Col-0 sample, compared to only 327 in *vir-1*.

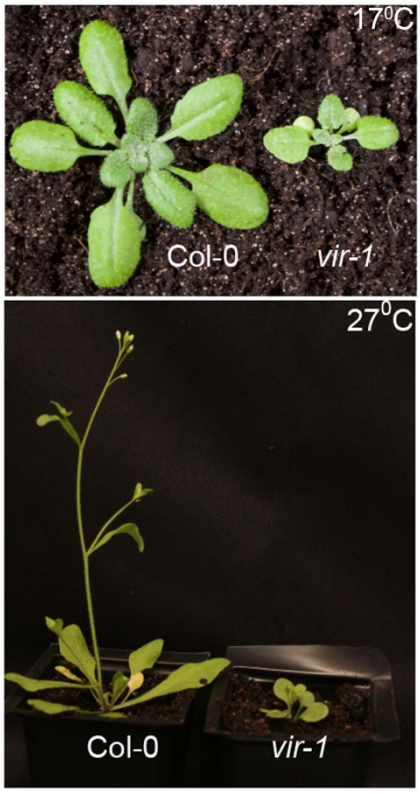


Figure 6: The primary visible developmental defects of *vir-1* mutants are not rescued by growth at 27°C

A) Developmental phenotype of Arabidopsis WT Col-0 and mutant *vir-1* grown at 17°C and 27°C. Plants are 28 days old and were grown at the indicated temperatures throughout their development following a 2-day stratification treatment.

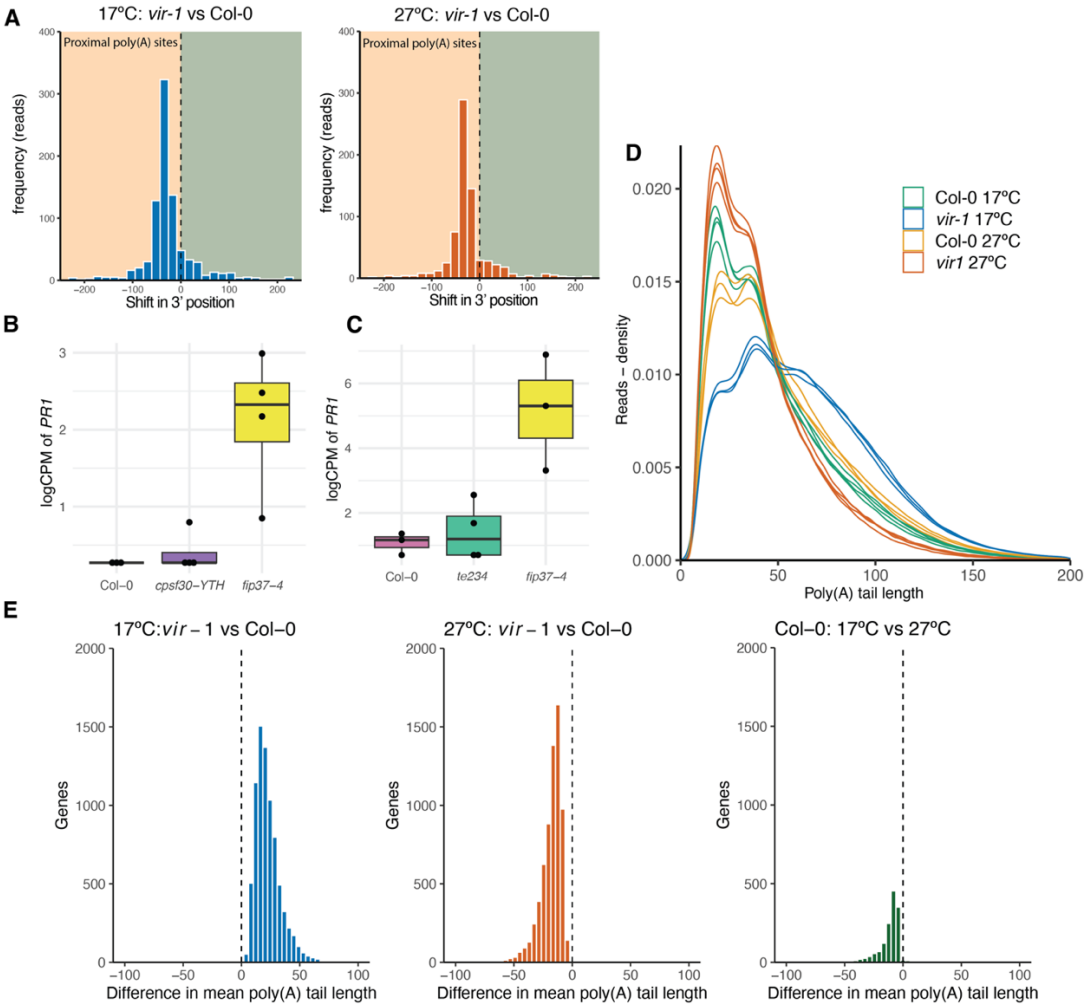
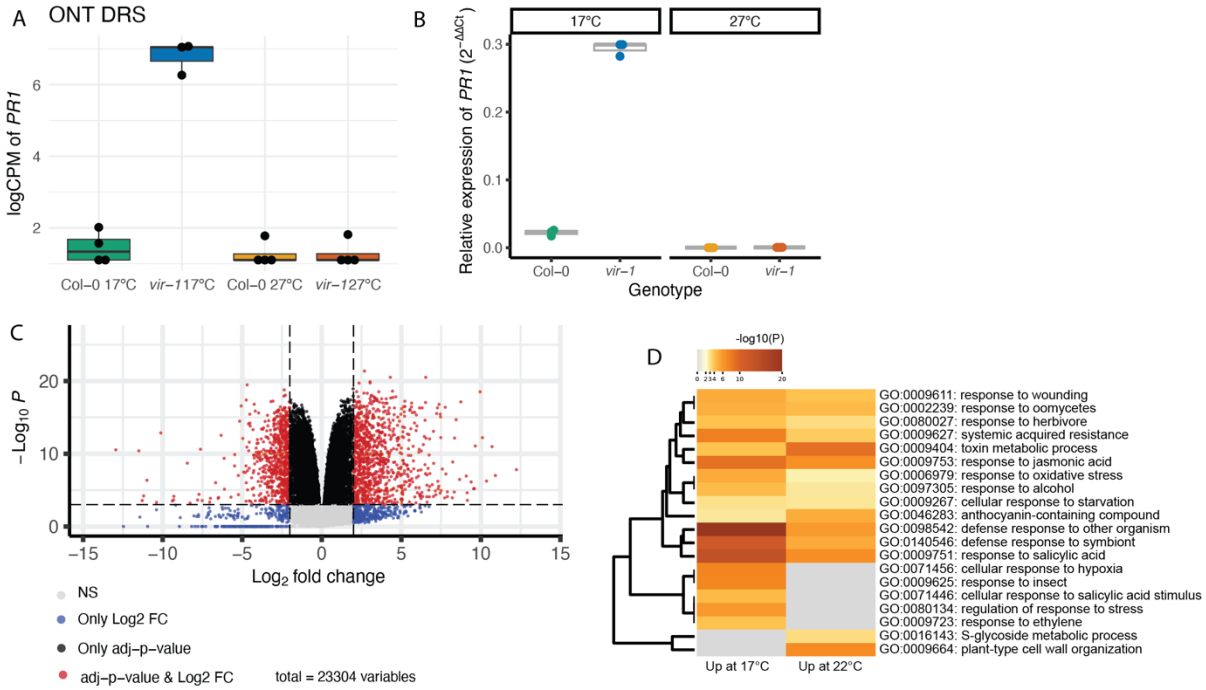


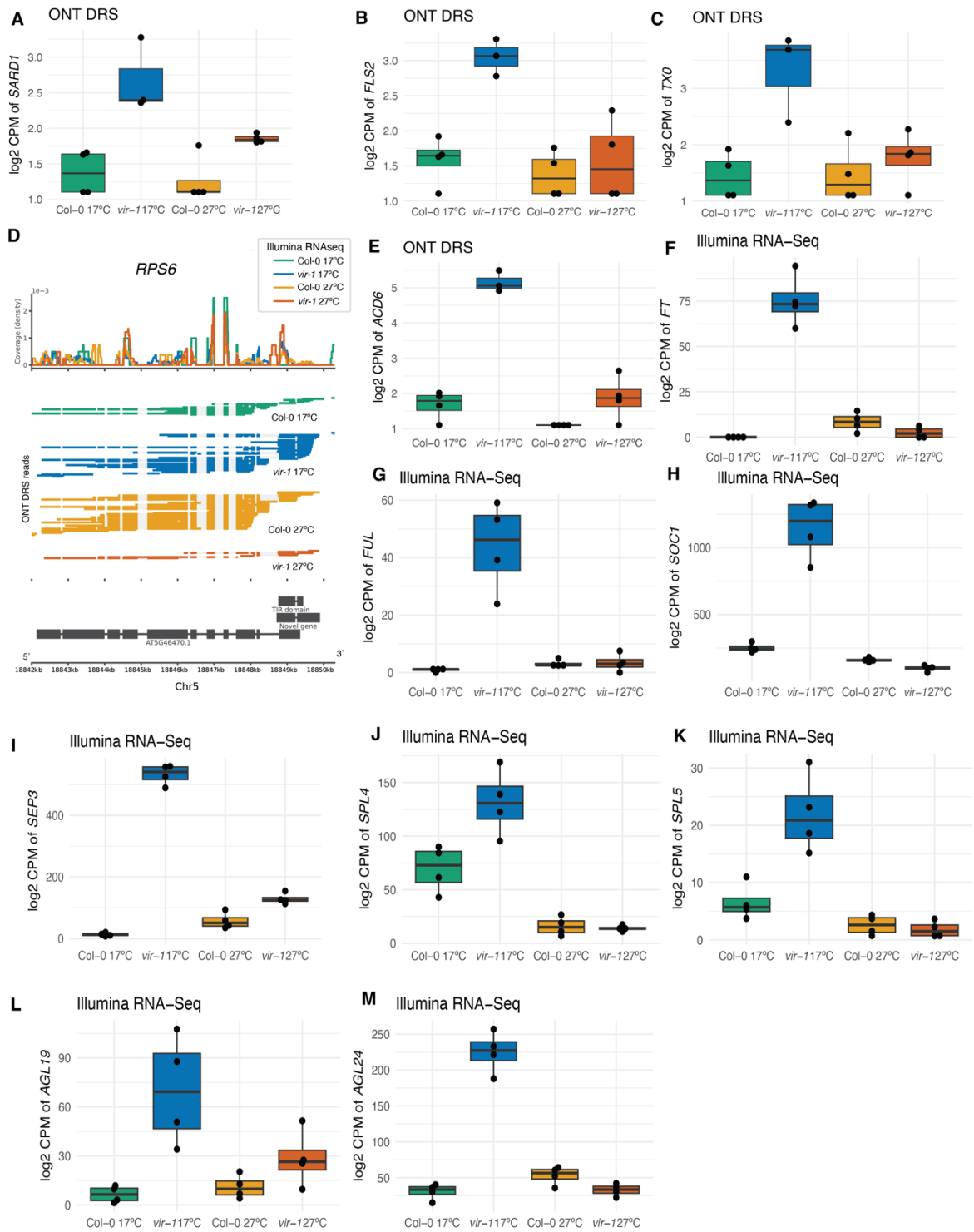
Figure 7: Poly(A) tail length distributions of *vir-1* are disrupted in a temperature sensitive manner

A) Shifts towards upstream (promoter-proximal) poly(A) site usage are detected in *vir-1* mutants at 17°C and 27°C compared to Col-0 WT. Source data available in Supplementary Table 14. B) Normalised expression (log 2 counts per million) of *PR1* (AT2G14610) in ONT DRS analysis of *cpsf30-yth* mutants at 20°C (n = 4 per condition). C) Normalised expression (log 2 counts per million) of *PR1* (AT2G14610) in ONT DRS analysis of *te234* triple mutants at 20°C (n = 4 per condition). D) Density distribution of poly(A) tail lengths in Col-0 and *vir-1* at 17°C and 27°C. The distribution of each replicate is plotted individually. E) Histograms depicting the distribution of Wasserstein distance metric for significant changes in mean poly(A) tail length per gene between Col-0 and *vir-1* at 17°C and 27°C, and between Col-0 at 27°C and 17°C. At 17°C, 13 genes have significantly shorter poly(A) tails in *vir-1*, while 7,894 genes have significantly longer tails. At 27°C, 6,669 genes displayed significantly shorter poly(A) tails in *vir-1*, whereas 7 genes had significantly longer tails. In Col-0 there are 1,425 genes with significantly shorter mean poly(A) tails at 17°C compared to 27°C. These findings are derived from data pooled across all replicates.



Supplementary Figure 2 – Linked to Figure 2

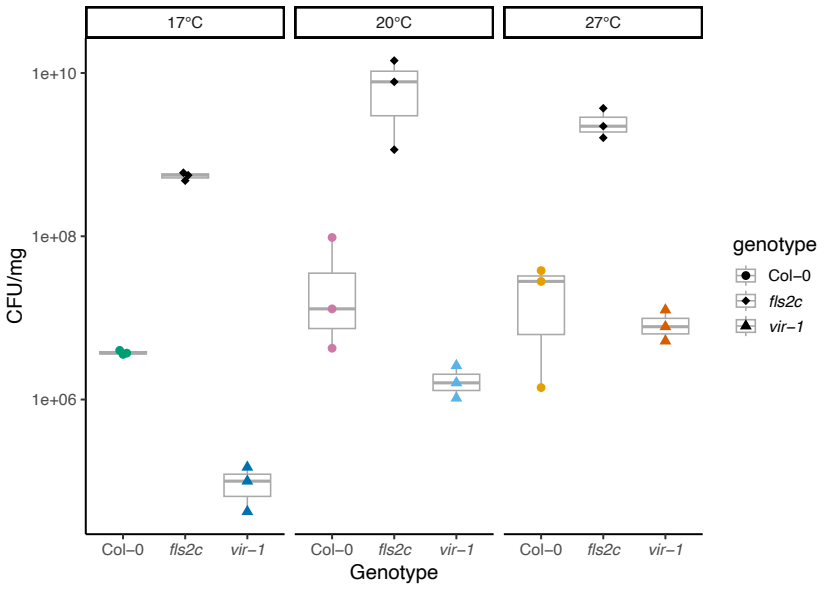
A) Normalised logged counts per million of *PR1* (AT2G14610) in Col-0 and *vir-1* 17°C and 27ºC (n = 3-4 per condition). B) RT-qPCR showing the upregulation of *PR1* in *vir-1* at 17°C (n = 3 per condition). C) Volcano plot showing the log2 fold change and adjusted p-value of differential gene expression in *vir-1* at 17°C contrasted to the average expression in *vir-1* at 27°C and Col-0 at 17°C and 27°C. Genes with log2FC > 2 and p < 0.001 are coloured in red, genes which only pass the p-value threshold are coloured in black, and genes which only pass the log2FC threshold are coloured in blue. Non-significant changes (NS) are coloured in grey. Source data available in Supplementary Table 5. D) Overlap in enriched GO terms between genes upregulated at 17°C contrasted to the average expression in *vir-1* at 27°C and Col-0 at 17°C and 27°C, and genes which were significantly upregulated in *vir-1* at 22ºC contrasted to Col-0 at 22ºC.



Supplementary Figure 3: Linked to Figure 3

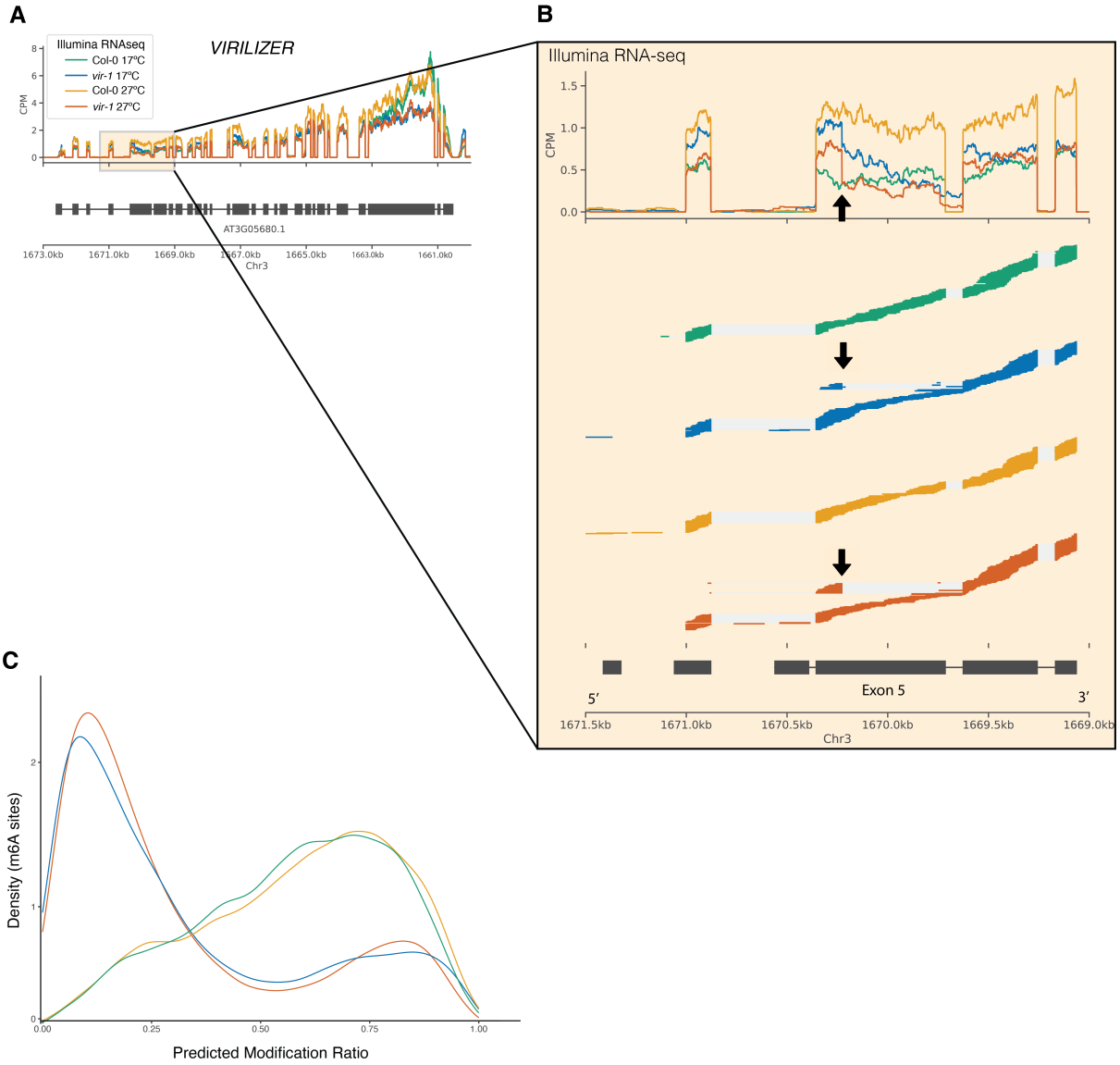
A) Upregulation of *SARD1* (AT1G73805) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log 2 counts per million) in ONT DRS data (n = 3-4 samples per condition). B) Upregulation of *FLS2* (AT5G46330) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log 2 counts per million) in ONT DRS data (n = 3-4 samples per condition). C) Upregulation of *TX10* (AT1G57630) in *vir-1* at 17°C, shown by a boxplot of normalised

expression (log 2 counts per million) in ONT DRS data (n = 3-4 samples per condition). D) Gene track of ONT DRS data showing the upregulation of a novel TIR domain-containing gene (annotated as Novel gene) downstream of *RPS6* (AT5G46470) in *vir-1* at 17°C (n = 3-4 samples per condition). E) Upregulation of *ACD6* (AT4G14400) in *vir-1* at 17°C, shown by a boxplot of normalised expression (log 2 counts per million) in ONT DRS data (n = 4 samples per condition). F-M) Boxplots showing the normalised log 2 counts per million (as produced by edgeR) for the flowering genes; *FT* (AT1G65480), *FUL* (AT5G60910), *SOC1* (AT2G45660), *SEP3* (AT1G24260), *SPL4* (AT1G53160), *SPL5* (AT3G15270), *AGL19* (AT4G22950) and *AGL24* (AT4G24540), in Illumina RNA-seq of *vir-1* and Col-0 at 17ºC and 27ºC (n = 4 samples per condition).



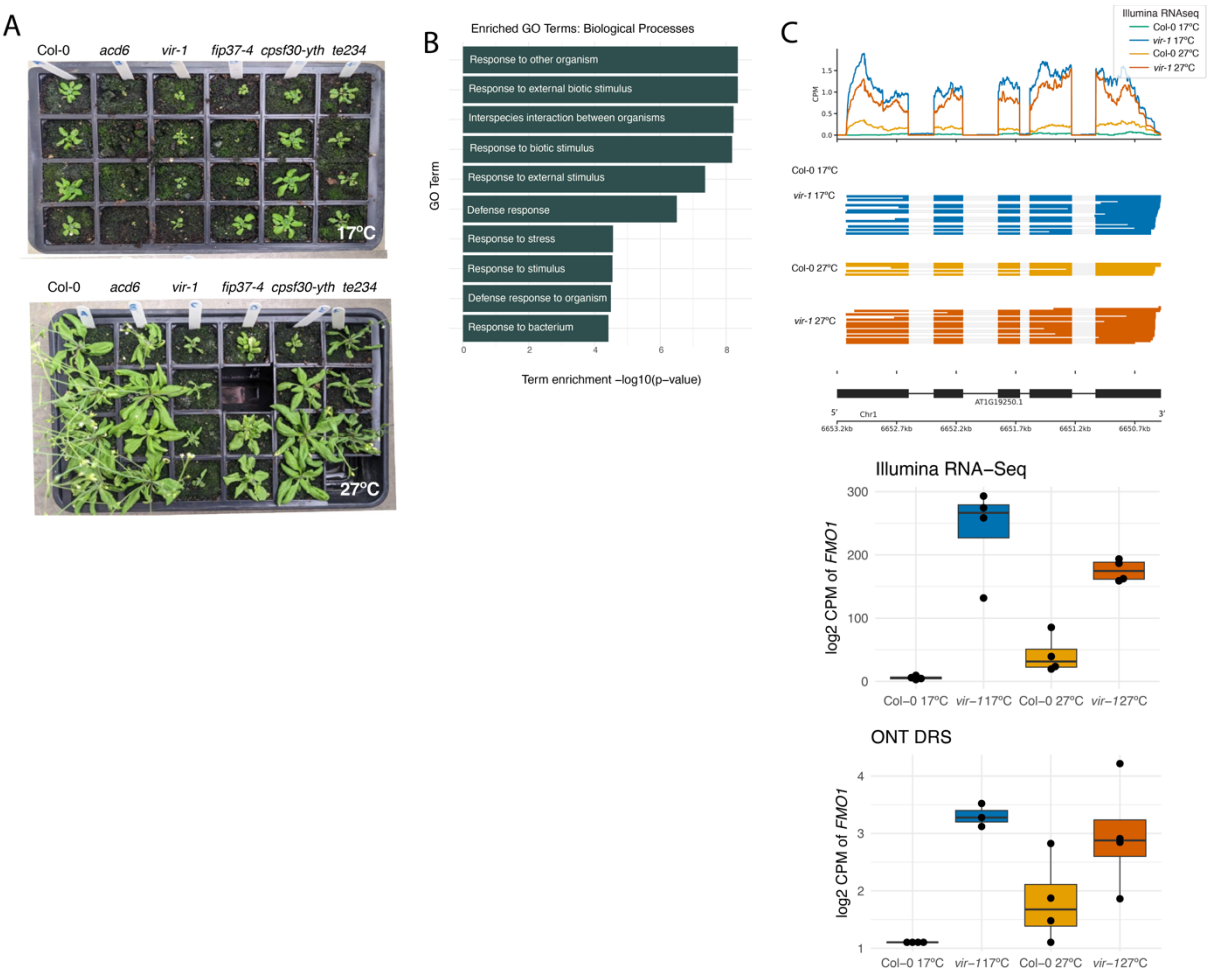
Supplementary Figure 4: Linked to Figure 4

Four-week-old Col-0 WT, *vir-1* and *fls2c* seedlings flood-inoculated with a bacterial suspension of *Pst* DC3000 ($5x10^6$ CFU/ml) and 0.025% v/v Silwet L-77. Bacterial populations were quantified at 3 days post inoculation (dpi) (n = 3 per condition). One way ANOVA tests on each genotype revealed a significant effect of temperature in the *vir-1* genotype (F = 23.02, p = 0.00197) which was not present in Col-0 WT or *fls2*. Source data available in Supplementary Table 9. This experimental analysis represents an independent replication of the experiment presented in Figure 4A.



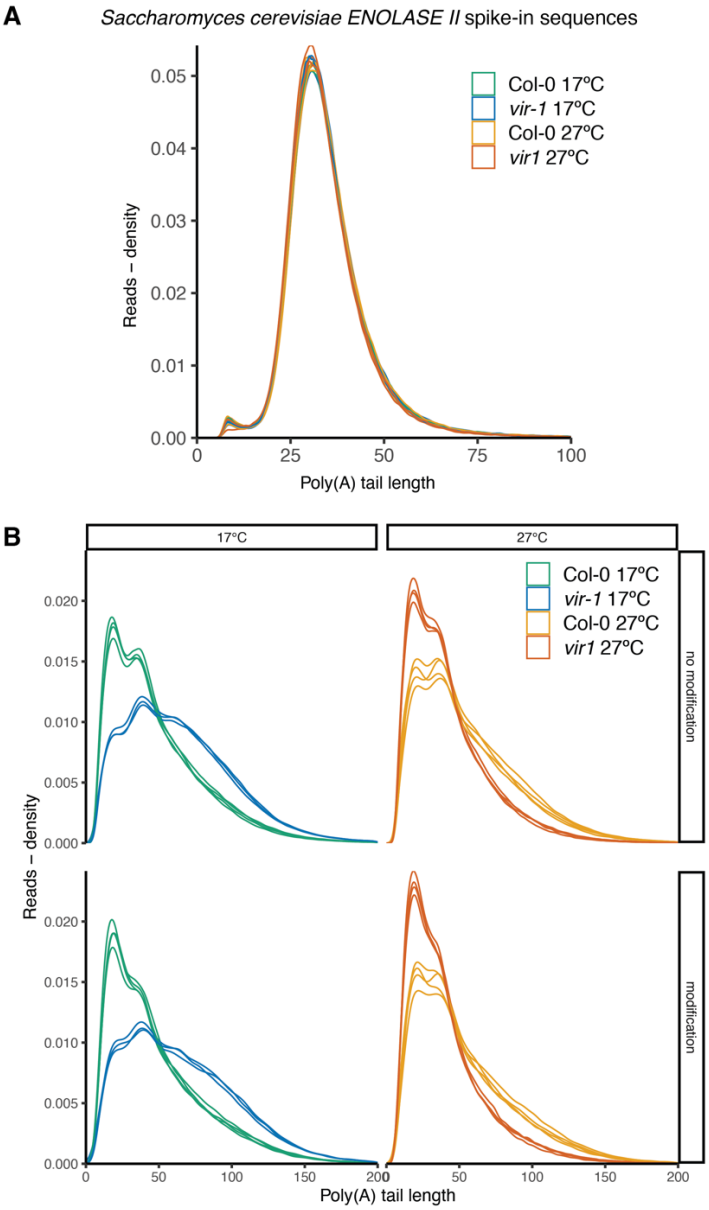
Supplementary Figure 5: Linked to Figure 5

A) Gene track showing the expression of *VIRILIZER* in Illumina RNA-seq *VIR* expression in *vir-1* mutants at 17°C and 27°C. B) Magnified portion of the *VIRILIZER* gene track showing the combined coverage and alignment of Illumina RNA-seq around the EMS point mutation in *vir-1*. The *vir-1* mutation affects the 5' splice site of intron 5 (G+1 to A), which leads to the activation of cryptic 5' splice sites upstream in exon 5 detected only in *vir-1* (denoted by an arrow). No suppression of this cryptic splicing is found at 27 °C. Aligned reads were subsampled to 200 reads per condition. C) Density distribution of the ratio of modification predicted by Yanocomp, for modifications with an FDR < 0.05. Predicted modification ratios for *vir-1* and Col-0 at 17°C were obtained by comparisons of *vir-1* at 17°C and Col-0 at 17°C. Predicted modification ratios for *vir-1* and Col-0 at 27°C were obtained by comparing *vir-1* at 27°C and Col-0 at 27°C.



Supplementary Figure 6: Linked to Figure 6

A) Phenotype of Col-0, *vir-1, fip37-4, cpsf30-yth, te234* and *acd6-1* grown at 17ºC and 27ºC. B) Gene ontology biological process terms enriched in the 58 genes consistently significantly upregulated (log2FC +/- 2.0 FDR < 0.001) in *vir-1* across 17°C, 20°C and 27°C compared to Col-0 and VIRc. Source data available in Supplementary Table 13. C) Upregulation of *FMO1* (AT1G19250) in *vir-1* at both 17°C and 27°C in Illumina RNA-seq and ONT DRS data, shown by gene tracks and boxplots of normalised expression (log 2 counts per million).



Supplementary Figure 7: Linked to Figure 7
A) Density distribution of poly(A) tail lengths of *Saccharomyces cerevisiae ENOLASE II* spike-in sequences in Col-0 and *vir-1* at 17°C and 27°C. *ENOLASE II* transcripts with a poly(A) tail length of 30 nt are included as the RNA calibration standard during ONT DRS library preparation. B) Density distribution of poly(A) tails in Col-0 and *vir-1* at 17°C and 27°C, divided into those belonging to genes with a predicted m^6A modification in Col-0 and those with no predicted modification. The distribution of poly(A) tails is plotted individually for each replicate.

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