Selinene volatiles are essential precursors for maize defense promoting fungal pathogen resistance

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List of Author contributions:

E.A.S., A.H. and Y.D. conceived the original screening and research plans; Y.D. performed most of the experiments; P.W. provided technical assistance to Y.D.; Y.D., T.G.K., C.A.M.R., J.L.S., A.E.L. designed the experiments and analyzed the data; E.A.S, Y.D. and A.H. conceived the project and wrote the article with contributions of all the authors; T.G.K., C.A.M.R., A.E.L. supervised and complemented the writing of specific sections.

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Abstract
To ensure food security, maize (Zea mays) is a model crop for understanding useful traits underlying stress resistance. In contrast to foliar biochemicals, root defenses limiting the spread of disease remain poorly described. To better understand below-ground defenses in the field, we performed root metabolomic profiling and uncovered unexpectedly high levels of the sesquiterpene volatile β-selinene and the corresponding non-volatile antibiotic derivative, β-costic acid. The application of metabolite-based Quantitative Trait Loci (mQTL) mapping using bi-parental populations, genome wide association studies, and near-isogenic lines (NILs) enabled the identification of terpene synthase 21 (ZmTps21) on chromosome 9 as a β-costic acid pathway candidate gene. Numerous closely examined β-costic acid deficient inbred lines were found to harbor Zmtps21 pseudo genes lacking conserved motifs required for farnesyl diphosphate (FPP) cyclase activity. For biochemical validation, a full length ZmTps21 was cloned, heterologously expressed in E. coli and demonstrated to cyclize FPP yielding β-selinene as the dominant product. Consistent with microbial defense pathways, ZmTps21 transcripts strongly accumulate following fungal elicitation. Challenged field roots containing functional ZmTps21 alleles displayed β-costic acid levels over 100 μg g<sup>-1</sup> FW, greatly exceeding in vitro concentrations required to inhibit the growth of five different fungal pathogens and rootworm larvae (Diabrotica balteata). In vivo disease resistance assays, using ZmTps21 and Zmtps21 NILs, further support the endogenous antifungal role of selinene-derived metabolites. Involved in the biosynthesis of non-volatile antibiotics, ZmTps21 exists as a useful gene for germplasm improvement programs targeting optimized biotic stress resistance.

Introduction
Plants are protected from a broad range of harmful biotic agents by initial perception events, signal transduction cascades and the elicitation of defense metabolism (Vanetten et al., 1994; Harborne, 1999; Dangl et al., 2013; Huffaker et al., 2013). In maize (Zea mays), seedlings are largely protected from attack by a complex suite of hydroxamic acid-based defenses, termed benzoxazinoids (BX), responsible for resistance to diverse threats spanning fungal pathogens and herbivores including Northern corn leaf blight (Setosphaeria turcica) and the European corn borer (ECB; Ostrinia nubilalis) (Beck et al., 1957; Couture et al., 1971; McMullen et al., 2009). Sixty years of research has resulted in a nearly complete metabolic and genetic BX pathway in maize involving over a dozen individual enzymes and metabolites (Frey et al., 2009; Meihls et al., 2013; Handrick et al., 2016). Additionally, diverse terpenoids and underlying terpene synthases (Tps) have also been demonstrated to play important protective roles (Degenhardt, 2009; Schmelz et al., 2014). As indirect defenses, herbivore-elicited terpene volatiles can function as diffusible signals to attract natural enemies, such as parasitoids and entomopathogenic nematodes, to above- and below-ground insect pests, respectively (Rasmann et al., 2005; Schnee et al., 2006).

Of the many biosynthetic classes of natural products, terpenoids are the most structurally diverse with well over 25,000 established compounds. In addition to roles as phytohormone signals, specialized terpenoids mediate inter-organism interactions and serve as chemical barriers (Gershenzon and Dudareva, 2007). In maize, terpene olefins are nearly ubiquitous components of
induced above and below-ground volatile emissions acting as indirect plant defenses following biotic stress (Turlings et al., 1990; Degenhardt, 2009; Degenhardt et al., 2009; Kollner et al., 2013). Maize terpene olefins can also serve as precursors for localized production of non-volatile antibiotic terpenoid defenses (Schmelz et al., 2014). While often undetectable at the level of volatile pathway intermediates, the inducible accumulation of non-volatile terpenoid end-products can limit the damage caused by fungi, herbivores and oxidative stresses (Harborne, 1999; Ahuja et al., 2012). Despite significant advances, continuing discoveries in maize reveals that our collective knowledge of biochemical defenses and pathway genes responsible for mitigating crop stress remains incomplete.

Decades of intensive research in related Poaceous crops, such as rice (*Oryza sativa*), has revealed multiple pathways of inducible labdane-related diterpenoids including momilactones, oryzalexins, and phytocassanes that underlay protective responses to biotic and abiotic stress (Schmelz et al., 2014). More recently, complex arrays of acidic terpenoids have been detected in maize and include sesquiterpenoids derived from β-macrocarpene and diterpenoids derived from ent-kauranes, termed zealexins and kauralexins, respectively (Huffaker et al., 2011; Schmelz et al., 2014). From a biosynthetic and pathway perspective, maize genes underlying the production of antifungal agents remain largely unknown. In the case of maize diterpenoid defenses, a specific ent-copalyl diphosphate synthase (Anther ear 2; ZmA2), is the only enzyme
demonstrated in planta essential for kauralexin biosynthesis (Vaughan et al., 2015).

To uncover further defense pathways, we employed targeted metabolomic profiling on field grown maize roots naturally exposed to combinations of herbivores and pathogens (Baldwin, 2012). Curiously, high levels of rarely encountered eudesmane sesquiterpenoids including β-selinene and β-costic acid dominated the chemical profiles of many samples. While not previously associated with maize, β-costic acid is known from the Asteraceae family, including false yellowhead (Dittrichia viscosa) and costus (Saussurea costus), and has been utilized in extracts for potent antibiotic activities against diverse organisms (Rao and Alvarez, 1981; Wu et al., 2006; Katerinopoulos et al., 2011). Despite the diverse phylogenetic occurrence in nature, a specific pathway predominantly leading to β-costic acid has not been described in plants. To explore the maize β-costic acid pathway, combined genetic mapping approaches with the intermated B73 x Mo17 (IBM) population of recombinant inbred lines (RILs) (Lee et al., 2002), the Goodman diversity panel (Flint-Garcia et al., 2005), and IBM near-isogenic lines (NILs) (Eichten et al., 2011) were used for metabolite-based Quantitative Trait Loci (mQTL) mapping. Biochemical characterization of the mQTL-identified Tps candidate utilized heterologous expression in E. coli to confirm identification of a comparatively product-specific β-selinene synthase. Transcript expression and metabolite analyses following elicitation with multiple pathogens and western corn rootworm (WCR, Diabrotica virgifera virgifera) larvae (Gray et al., 2009; Meinke et al., 2009; Miller et al.,
2009; Spencer et al., 2009; Tinsley et al., 2013) were used to assess pathway activation. Concentrations of β-costic acid below those detected in field tissues were then used to examine \textit{in vitro} antibiotic activity against 5 fungal species. Similarly, NILs were used to investigate \textit{in vivo} root resistance following challenge with \textit{Fusarium verticillioides} and \textit{Fusarium graminearum}. Collectively our results support the existence of a previously unrecognized β-costic acid pathway in maize that contributes to fungal pathogen resistance.

\section*{RESULTS}

\textbf{Identification of α and β-selinene derived products as inducible maize sesquiterpenoids that can influence generalist root herbivores.} Our previous investigation of maize responses following stem herbivory and fungal elicitation enabled the discovery of two distinct biosynthetic classes of inducible acidic terpenoids (Huffaker et al., 2011; Schmelz et al., 2011). Similarly, experiments examining maize root defenses elicited by banded cucumber beetle (\textit{Diabrotica balteata}) larvae and \textit{F. verticillioides} infection confirmed shared responses in diverse tissue types (Vaughan et al., 2015). Given that predominant defenses change over ontogeny and that controlled lab experiments do not capture the full suite of biotic stresses in nature (Kollner et al., 2004; Baldwin, 2012), we sought to expand our targeted metabolomic analyses to roots in the context of natural biotic challenge (Schmelz et al., 2004). As expected, mature visibly-necrotic roots of field-challenged maize lines including hybrid sweet corn (var. Golden Queen) and the inbred Mo17 contained zealexins (Fig. 1A); however, chemically...
extracted samples unexpectedly also contained α-selinene, β-selinene, β-costol, α-costic acid and β-costic acid (Fig. 1; Supplemental Fig. S1). In volatile collections of live Mo17 root emissions, α-selinene, β-selinene (Fig. 2) and the aldehyde β-costal (Supplemental Fig. S1) were likewise detectable. As the major analyte, live field-collected Mo17 roots displaying visible necrosis emit predominantly β-selinene (Fig. 2). In contrast, β-selinene emission is absent in B73 roots; however, production reappears in select B73 x Mo17 RILs, for example IBM0287 (Fig. 2). Similar volatile emission results are observed in live Mo17 stems following inoculation with the necrotrophic fungal pathogen (Cochliobolus heterostrophus), commonly known as southern leaf blight (SLB) (Fig. 2). Consistent with root metabolite patterns, the reference genome inbred B73 (Schnable, 2009) remains void of α and β-selinene stem volatiles under identical conditions (Fig. 2). Qualitative metabolite differences between B73, Mo17 and select RILs provides empirical evidence for genetic variation in selinene biosynthesis and encourages the use of genetic mapping resources (Lee et al., 2002).

Our quantification of unexpectedly high levels of β-selinene and β-costic acid in field collected maize roots was paired with casual field observations of adult D. balteata beetles on leaves. Given the broad host range of D. balteata larvae (Saba, 1970) and pest pressures exerted by western corn rootworm (WCR: Diabrotica virgifera virgifera) larvae including the promotion of secondary disease (Flint-Garcia et al., 2009; Gray et al., 2009), we conducted controlled Diabrotica-maize interaction experiments. In growth chamber assays, tissue
extracts of roots revealed both β-selinene and β-costic acid following damage by WCR larvae (Fig. 2). Given the high levels of selinene-derived metabolites observed in field-collected roots, additional assessments of WCR and *D. balteata* preference and performance were conducted on larvae. For both *Diabrotica* species, we observed no influence of exogenously applied β-costic acid on root preference but found a significant inhibitory role of β-costic acid on *D. balteata* performance (Fig. 2).

**Combined linkage and association mapping identifies maize terpene synthase *ZmTps21* as a candidate biosynthetic gene.** β-selinene has been previously detected in the volatile profiles of pathogen-challenged maize tissue; however, the biosynthetic source and physiological function(s) have not been elucidated (Becker et al., 2014). Given our observation that selinene-derived pathway products can predominate in maize under specific conditions, we sought to identify the gene(s) responsible. We first employed the IBM-RILs for mQTL mapping. As a predictable non-volatile pathway end product, β-costic acid levels were analyzed in naturally challenged roots of 216 IBM RILs (Supplemental Table S1). Composite Interval Mapping (CIM) placed the locus in Bin 9.05 (Fig. 3) (Gardiner et al., 1993). For comparative purposes, the IBM-RIL data was also explored using 173,984 SNPs and association mapping via a General Linear Model (GLM) (Bradbury et al., 2007) and Unified Mixed Linear Model (MLM) (Yu et al., 2006). All approaches supported a single statistically significant locus on chromosome 9 (Fig. 3, Supplemental Fig. S2). Additionally we performed an
elicited metabolite-based Genome-Wide Association Study (mGWAS) using β-costic acid levels in greenhouse grown inbreds from the Goodman diversity panel (Flint-Garcia et al., 2005). Similarly, we detected a single statistically significant locus on chromosome 9 (Fig. 3). An independent mGWAS replication conducted with field grown plants yielded an identical result (Supplemental Fig. S2). Correspondence of physical QTL coordinates identified with IBM RILs and the replicated GWAS results (Fig. 3, Supplemental Fig. S2) robustly supported a single narrow locus controlling maize β-costic acid levels.

For additional confirmation, select B73×Mo17 near isogenic lines (NILs) were analyzed following stem elicitation (Eichten et al., 2011). B73 chromosomal segments introgressed into Mo17 dominating lines (specifically m012, m048, m050 and m062) were each deficient in the production of β-costic acid (Fig. 3). In contrast, β-costic acid production in NILs with introgressions of the Mo17 allele into the B73 genetic background (lines b047, b055, b069, and b157) were similar to Mo17 (Fig. 3, Supplemental Fig. S3), confirming existence of the β-costic acid associated locus in Bin 9.05. Further analyses of additional NIL lines (b022, b033, m002, m065, and m092) narrowed the locus to 13 predicted genes isolated on bacterial artificial chromosome (BAC) clones, AC213878 and AC204415 (Fig. 3). Of the remaining candidates, only a single uncharacterized gene (GRMZM2G011151) displayed significant sequence homology with known terpene synthases. Supportively, detailed examination of 3 independent association mapping results likewise demonstrated the presence of highly significant SNPs associated with the Tps candidate (GRMZM2G011151), termed
ZmTps21 (Supplemental Fig. S2). Genomic structure analysis of B73 Zmtps21 revealed three predicted exons encoding a 297 amino acid protein lacking the conserved Tps catalytic domains, namely the DDXXD and RXR motifs (Fig. 3), which are essential for function (Chen et al., 2011). Collectively, these findings made B73 Zmtps21 a parsimonious inactive β-selinene synthase pseudogene candidate meriting further examination.

In an attempt to isolate the Mo17 ZmTps21 cDNA sequence, early RT-PCR trials with primers based upon B73 Zmtps21 cDNA failed due to nucleotide polymorphisms. Eventually a segment near the Mo17 ZmTps21 5'-end of genomic DNA of was obtained by a PCR and sequenced. Alignments revealed that the segment near the Mo17 ZmTps21 5'-end DNA fragment shared high sequence similarity to that of B73 Zmtps21. Therefore, the 5'-end cDNA sequence of Mo17 ZmTps21 was obtained by RT-PCR and extended by PCR with rapid amplification of cDNA ends (rPCR) using a cDNA library to obtain the full-length Mo17 ZmTps21 cDNA (Fig. 3; Supplemental Fig. S4). The deduced amino acid sequence of the open reading frame contained the conserved terpene synthase domains including the DDXXD (residues 325 to 329) and RXR (residues 288 to 290) motifs (Supplemental Fig. S4). The amino acid sequence of ZmTps21 resembles (<60% identity) those of other plant sesquiterpene synthases and shares less than 40% sequence identity with previously characterized maize sesquiterpene synthases, such as ZmTps6, ZmTps10, ZmTps11, and ZmTps23 (Supplemental Fig. S4). With only 30% identity at the amino acid level, Mo17 ZmTps21 is even more distantly related to the Ocimum
basilicum sesquiterpene synthase (SES) which produces detectable levels of β-selinene as part of a complex blend (Supplemental Fig. S4) (Iijima et al., 2004).

To understand the extent of genetic variation in ZmTps21 alleles, we examined 15 commonly investigated inbreds. ZmTps21 genomic sequences were isolated by PCR using primers based on the B73-Zmtps21 and Mo17-ZmTps21 genome sequences, respectively (Supplemental Table S1). Sequence analyses demonstrated that the Zmtps21 alleles from B73-like lines (Ki3, M37W, MS71, M162W, CML247, Ki11, Mo18W) share >98% DNA sequence identity and basic genome structure, whereas Mo17-like ZmTps21 alleles (Hp301, TX303, Oh43, Oh7B, Ky21 and W22) contain six exons and share higher than 98% sequence identity at the amino acid level (Supplemental Fig. S5 and S6). These results support the hypothesis that B73-like inbred lines share a common mutation ancestry.

In vitro assays demonstrate that ZmTps21 is a largely product-specific β-selinene synthase. ZmTps21 lacks a predicted N-terminal transit peptide suggesting that the enzyme is not targeted to plastids as is typical of monoterpene and diterpene synthases, but instead remains cytosolic consistent with predictions for a sesquiterpene synthase (Gershenzon, 1999). To obtain additional support for the hypothesis that Mo17 ZmTps21 is a β-selinene synthase, heterologous expression was performed in E. coli and the resulting protein extract was incubated with the precursor substrate (E,E)-farnesyl diphosphate (FPP). β-selinene is the dominant product observed by GC-MS.
along with several other minor sesquiterpene olefins, including \( \alpha \)-selinene and \( \beta \)-elemene (Fig. 4). Thus ZmTps21 encodes a selinene synthase with predominant \( \beta \)-selinene product specificity that includes \( \alpha \)-selinene as a minor product consistent with the olefin and oxygenated metabolite ratios observed in planta (Fig. 1, Supplemental Fig. S1). Injection of the ZmTps21 reaction products on a GC column at different temperatures revealed that the \( \beta \)-elemene present is due to a Cope rearrangement of germacrene A (Supplemental Fig. S7 and S8) (de Kraker et al., 2001). Germacrene A also is a neutral reaction intermediate of the tobacco (Nicotiana tabacum) enzyme 5-\( epi \)-aristolochene synthase (TEAS) responsible for the pathogen-elicited biosynthesis of capsidiol (Cane, 1990; Starks et al., 1997). The enzymatic protonation of germacrene A leads to the eudesmane carbocation further converted to 5-\( epi \)-aristolochene. Given that \( \beta \)-selinene is simply formed by a deprotonation of a eudesmane carbocation, it likely that the reaction catalyzed by ZmTps21 also includes the formation and protonation of germacrene A. A sequence comparison of ZmTps21 with TEAS and other Tps able to protonate neutral reaction intermediates demonstrate that the amino acids of the catalytic triad involved in the protonation reaction are conserved (Starks et al., 1997) (Supplemental Fig. S4). Curiously, two ZmTps21 mutants with altered C-termini obtained as cloning artifacts produced only germacrene A (Supplemental Fig. S7 and S8), suggesting additional influence of the C-terminus on the protonation reaction and specificity of the final product.
ZmTps21 transcripts are pathogen inducible and correspond with β-costic acid accumulation. To examine endogenous patterns, we compared Mo17 ZmTps21 expression with established ZmTps6/11 expression associated with zealexin biosynthesis (Kollner et al., 2008; Huffaker et al., 2011). Similar to ZmTps6/11-zealexin relationships, ZmTps21 transcripts and β-costic acid are barely detectable in control tissues and not significantly elicited by mechanical damage alone (Fig. 5). After elicitation with heat-killed Fusarium hyphae, ZmTps6/11 transcripts reached maximal levels at day 1 while ZmTps21 transcripts levels continued to accumulate for an additional day (Fig. 5). Zealexin A1 was readily detectable at day 1 and continued to increase over the 4 days while β-costic acid accumulation was first detected at day 2 reaching similar levels at day 4 (Fig. 5). Thus, ZmTps21 transcripts and product accumulation display longer-term and temporally layered elicitation kinetics alongside the zealexin biosynthetic pathway.

To examine whether ZmTps21 transcripts and β-costic acid levels change specifically in response to aggressive pathogens such as C. heterostrophus and F. verticillioides or whether the response also follows opportunistic fungi such as Rhizopus microsporus and Aspergillus parasiticus, both parameters were analyzed in inoculated stems. Exposure to C. heterostrophus, F. verticillioides, R. microsporus, and A. parasiticus all resulted in significant induction of both ZmTps6/11 transcript levels and zealexin A1, which vary in response to different fungi (Fig. 5) (Huffaker et al., 2011). In the same context the 4 fungal species also led to significant accumulation of ZmTps21 transcripts and β-costic acid.
Infection with *C. heterostrophus* led to the highest induction of both *ZmTps21* transcripts and β-costic acid in stems, similar to *ZmTps6/11* transcripts and zealexin levels, respectively (Fig. 5). To further consider the natural occurrence of β-selinene derived metabolites in diverse inbreds (McMullen et al., 2009) we analyzed the scutella tissues of 10-d old seedling plants. β-costic acid was detected in all lines harboring Mo17-like *ZmTps21* alleles (Hp301, TX303, Oh43, Oh7B, Ky21, and W22) and was comparatively absent from all inbreds harboring B73-like *Zmtps21* (Ki3, M37W, MS71, M162W, CML247, Ki11, Mo18W) pseudogenes (Fig. 5; Supplemental Fig. S5 and S6). Collectively, these results support the existence of a single β-selinene synthase in maize responsible for the production of β-costic acid.

**In vitro and in vivo assays support a defensive role for β-costic acid in fungal disease resistance.** In effort to assess physiological roles, we quantified β-costic acid present in replications of field-collected roots of B73, Sweet corn (var. Golden Queen), Mo17 and the *ZmTps21* IBM-RIL 0287. On average, sectors of roots containing visible necrosis from each responsive line contained well over 100 µg g⁻¹ FW of β-costic acid (Fig. 5). Using this conservative baseline, we then examined the antimicrobial activity of β-costic acid against *F. verticillioides*, *F. graminearum*, *R. microsporus*, *A. parasiticus*, and *C. heterostrophus* in liquid culture assays. At 100 µg ml⁻¹, β-costic acid completely inhibited the growth of *R. microsporus* and significantly suppressed the growth of all other fungi (Fig. 6; Supplemental Fig. S9). Importantly, β-costic acid
concentrations as low as 25 µg ml\(^{-1}\) retained significant inhibitory activity in each case demonstrating that β-costic acid has the potential to function as wide-spectrum antifungal defense at low doses. To estimate \textit{in vivo} roles, mature roots of greenhouse grown B73, Mo17 and 2 predominantly Mo17 IBM-NILs (Supplemental Fig. S9) where damaged and treated with either H\(_2\)O or H\(_2\)O containing spores of \textit{F. verticillioides} and \textit{F. graminearum} separately. Seven days later, the B73 inbred and the IBM-NIL (m050) harboring a \textit{Zmtps21} pseudogene displayed significantly greater levels of disease as estimated by \textit{Fusarium} DNA levels compared to Mo17 and the functional \textit{ZmTps21} IBM-NIL (m065) (Fig. 6). Collectively, our results are consistent with \textit{ZmTps21} pathway products as mediators of antifungal defenses.

**Discussion**

Maize biochemicals either demonstrated or predicted to mediate insect and pathogen defense include diverse volatiles (Degenhardt, 2009; Degenhardt et al., 2009), benzoxazinoids (Frey et al., 2009; Ahmad et al., 2011; Meihls et al., 2013; Handrick et al., 2016), flavonoids and C-linked flavonoid glycosides (Meyer et al., 2007; Balmer et al., 2013; Casas et al., 2016), non-protein amino acids (Yan et al., 2015), oxylipins (Christensen et al., 2015; Borrego and Kolomiets, 2016), and non-volatile terpenoids (Schmelz et al., 2014). Among all biosynthetic classes, terpenoids are the most diverse structurally and in demonstrated breadth of ecological interactions mediated (Gershenzon and Dudareva, 2007). At the genome level, plants commonly possess mid-sized terpene synthase gene...
families ranging from 14 to 70 members (Chen et al., 2011). More specifically, in maize use of “terpene” as a keyword search in Phytozome (https://phytozome.jgi.doe.gov) currently reveals more than 30 Tps gene models. Collective efforts have resulted in the genetic, biochemical and ecological characterization of approximately half of the maize enzymes encoded by Tps with product specificity in the production of mono-, sesqui- and diterpenes (Schnee et al., 2002; Kollner et al., 2004; Schnee et al., 2006; Kollner et al., 2008; Degenhardt et al., 2009; Fu et al., 2016; Richter et al., 2016). Maize terpene volatiles are often highly inducible following insect attack and aid in the attraction of diverse natural enemies both above and below ground (Turlings et al., 1990; Rasmann et al., 2005; Degenhardt et al., 2009). Oxygenated non-volatile terpenoids can also accumulate and act as antifungal agents and insect antifeedants (Schmelz et al., 2011). As part of this biochemical complexity, we demonstrate that maize tissues are capable of accumulating both high levels of the sesquiterpene olefin β-selinene and the corresponding non-volatile oxygenated derivative termed β-costic acid. Intriguingly, β-costic acid is produced in diverse aromatic and medicinal plants widely investigated for bioactive agents driving antibiotic and anti-arthropod activities (Rao and Alvarez, 1981; Wu et al., 2006; Katerinopoulos et al., 2011). Despite the widespread occurrence in nature, Tps essential for the specific in vivo production of β-costic acid have not been previously demonstrated in planta. We currently describe a maize β-selinene synthase, termed ZmTps21, which is required for the inducible accumulation of β-costic acid.
High tissue concentrations of β-costic acid were first detected in mature field-collected roots of both sweet corn and Mo17 but appeared absent the B73 inbred. Use of complimentary mapping resources and the induced production of β-costic acid as a qualitative trait demonstrated single a narrow QTL containing a Tps gene candidate.

To examine the full-length Mo17 ZmTps21 allele identified, heterologous expression experiments were conducted in E. coli and protein extracts incubated with FPP yielded β-selinene as the dominant volatile product. Based on numerous inbred lines and predicted proteins from genome sequences (Supplemental Fig. S5 and S6), the in vitro products of functional ZmTps21 are consistent with the endogenous presence of β-costic acid in all Mo17-like ZmTps21 lines and likewise an absence in all B73-like Zmtps21 lines (Fig. 5).

Precursors of dominant biochemical defense pathways are commonly the products of fully functional duplicate genes (Kollner et al., 2008; McMullen et al., 2009); however, mGWAS mapping results (Fig. 2) and the exclusive presence of β-costic acid (Fig. 5) in lines with full-length ZmTps21 alleles collectively support the existence of a single maize β-selinene synthase. At the enzymatic level, the existence of a product specific β-selinene synthase was first reported in 1992 through the examination of Citronella mitis fruits; however, the specific Tps gene responsible remains unknown (Belingheri et al., 1992). Acid-induced cyclization of germacrenes can also yield selinenenes making it highly probable that a germacrene A synthase is responsible for the costol, costal, and costic acid eudesmanes in costus root oil; however, it remains unknown if costus contains a
specific β-selinene synthase (de Kraker et al., 2001). Further elucidation of the β-
costic acid pathway will require the discovery of a yet unresolved cytochrome
P450 monooxygenase(s) performing sequential oxidations leading to the
carboxylic acid. Characterized germacrene A oxidases from the Asteraceae drive
the biosynthesis of germacrene A acid which following acid-induced
rearrangement can yield blends that include β-costic acid (Nguyen et al., 2010).
A related P450 that directly oxidizes β-selinene to yield β-costic acid is predicted
to occur in maize yet remains unknown.

While numerous plants in nature constitutively make β-selinene in specific
tissues and life stages, β-selinene is rarely detected in maize and has occurred
only in the context of pathogen attack (Becker et al., 2014; Sowbhagya, 2014).
Consistent with this observation we find ZmTps21 transcripts largely
undetectable in healthy control tissues or those experiencing simple mechanical
damage (Fig. 5). In contrast, heat-killed Fusarium hyphae and a wide range of
live fungal species elicit ZmTps21 transcript accumulation and β-costic acid
production. With conceptual similarities to the zealexin pathway, the elicitation
kinetics of both ZmTps21 transcripts and β-costic acid differ and are temporally
behind those of ZmTps6/11 and zealexins. Given the broader range of fungi
species displaying β-costic acid mediated growth suppression at 25 µg ml⁻¹
compared to similar assays using zealexins (Huffaker et al., 2011), it is possible
that the ZmTps21 pathway exists as an additional potent line of defense
activated sequentially as maize plants experience sustained attack. If this
hypothesis is true, related studies on maize disease resistance should note
biological roles for QTLs that include *ZmTps21*. Supportively, independent disease-related QTLs have been detected in broad regions spanning Bin 9.05 (Baumgarten et al., 2007; Berger et al., 2014). More specifically *ZmTps21* (GRMZM2G011151) has been identified as uniquely present in transcriptome analyses of resistant inbred lines associated with enhanced antifungal defenses (Lanubile et al., 2014). In an empirical assessment of the *in vivo* role of *ZmTps21* derived defenses, root experiments using B73, Mo17 and 2 Mo17 NILs support the suppression of both *F. graminearum* and *F. verticillioides* growth in lines carrying functional Mo17 *ZmTps21* alleles (Fig. 6). Most maize biochemical defenses likely function in the context of complex arrays of bioactive metabolites from numerous pathways. In this context, isogenic mutants in numerous inbred backgrounds would be an ideal and improved platform for the critical examination of *ZmTps21* mediated biological functions. While the present study does not accomplish this long-term goal, we provide a foundation and mechanistic justification for related research directions.

Curiously, of lines closely examined at the gene level, β-costic acid biosynthesis mediated by *ZmTps21* is associated with inbreds originating from U.S. breeding programs. In contrast, β-costic acid biosynthetic capacity is largely absent from more geographically diverse accessions. It is tempting to speculate that while the β-costic acid pathway is commonly absent due to a partial gene deletion, *ZmTps21* may have been maintained by positive selection during the breeding of U.S. maize lines. Western corn rootworm (WCR: *Diabrotica virgifera virgifera*) larvae exist as a candidate pest pressure known to devastate the roots.
of temperate maize through below-ground herbivory and the promotion of secondary disease (Flint-Garcia et al., 2009; Gray et al., 2009). In growth chamber experiments, maize plants containing a functional \textit{ZmTps21} allele produced both \( \beta \)-selinene and \( \beta \)-costic acid following damage by WCR larvae (Fig. 2). Consistent with a long-term association, unlike the generalist \textit{D. balteata}, WCR larvae were not significantly affected in preference or performance by \( \beta \)-costic acid as a direct defense (Fig. 2). In this context, \( \beta \)-costic acid is likely to be more important in limiting the secondary spread of fungal pathogens promoted by root herbivory. However, while not specifically examined here, we speculate that root pools of \( \beta \)-selinene may serve as a volatile attractant to natural enemies of \textit{Diabrotica} larvae such as entomopathogenic nematodes (Rasmann et al., 2005; Degenhardt et al., 2009). This phenomena has been demonstrated in context of trace amounts of maize root caryophyllene elicited following WCR larval herbivory. More broadly, numerous root terpene volatiles can attract both entomopathogenic and phytopathogenic nematodes, a result that highlights complex tradeoffs in the deployment of rhizosphere signals (Ali et al., 2011).

In conclusion, our current study identifies the presence of numerous \( \alpha/\beta \)-selinene derived metabolites in maize tissues following biotic stress. In numerous trials using select maize lines, \( \beta \)-selinene and \( \beta \)-costic acid exist as predominant \textit{ZmTps21}-derived terpenoids produced following fungal elicitation, long-term root herbivory and combined field pressures. Antifungal assays using both \textit{in vitro} and \textit{in vivo} approaches support an antifungal defense role for \textit{ZmTps21} pathway products. Root herbivores are likely to be additionally impacted given that \( \beta \)-
costic acid can reduce the performance of generalists such as *D. balteata* in controlled bioassays. The discovery of further immune-related biochemical traits is certain to continue given the extreme genetic diversity in maize highlighted by over 8000 representative transcript assemblies detectable in diverse germplasm that are absent from B73 (Hirsch et al., 2014). To fill existing voids highlighted by comparative genomics, the combined application of metabolomics, mapping, and *in vitro* biochemistry provides a useful approach to rapidly connect phenotypes with genotypes (Meihls et al., 2013; Handrick et al., 2016; Richter et al., 2016). Our current identification of ZmTps21 as a $\beta$-selinene synthase required for $\beta$-costic acid production adds to the foundational knowledge of useful maize biochemical pathways that can be intentionally combined for combating complex biotic pressures.

**MATERIALS AND METHODS**

**Plant and Fungal Materials**

Seeds of the Intermated B73×Mo17 (IBM) population of recombinant inbred lines (RILs) and the Goodman diversity panel (Flint-Garcia et al., 2005) were kindly provided by Dr. Peter Balint-Kurti (USDA-ARS, Raleigh, NC, USA) and Dr. Georg Jander (Boyce Thompson Institute, Ithaca, NY, USA) (Supplemental Table S2). The IBM-RILs and Goodman diversity panel (replicate 2) were planted at the Biology Field Station located on the University of California San Diego (UCSD) campus in La Jolla, CA, USA, during the summers of 2015 and 2016, respectively. Field challenged roots from B73, Mo17, hybrid sweet corn (*Zea*
mays var. Golden Queen; Southern States Cooperative, Inc. Richmond, VA, USA) and IBM RILs were recovered 70 days after planting, washed, frozen in liquid N₂, ground to a fine powder and ultimately used for genetic mapping.

Seeds of indicated B73×Mo17 near-isogenic lines (provided by the Maize Genetic COOP Stock Center, Urbana, IL, USA), landrace inbreds (B73, Ki3, M37W, Ms71, M162W, CML247, Ki11, Mo18W, Hp301, TX303, Oh43, Oh7B, Ky21, Mo17, and W22; National Genetic Resources Program, Germplasm Resources Information Network, Ames, IA) were germinated in MetroMix 200 (Sun Gro Horticulture Distribution, Inc.) supplemented with 14-14-14 Osmocote (Scotts Miracle-Gro) and grown in a greenhouse as previously described (Schmelz et al., 2009) (Supplemental Table S2). Fungal stock cultures of Rhizopus microsporus (Northern Regional Research Laboratory stock no. 54029), Fusarium verticillioides (Northern Regional Research Laboratory; NRRL stock no. 7415), Fusarium graminearum (NRRL stock no. 31084) Aspergillus parasiticus (nor-1), and Cochliobolus heterostrophus were grown on V8 agar for 12 days before the quantification and use of spores (Huffaker et al., 2011; Huffaker et al., 2013). Heat-killed Fusarium venenatum (strain PTA-2684) hyphae was commercially obtained (Monde Nissin Corporation Co.) and used safely for large-scale field mGWAS trials as a non-infectious elicitor lacking known Fusarium mycotoxins.

Genetic Mapping of ZmTps21
Using the presence of $\beta$-costic acid in necrotic tissues as a trait, the B73
Zmtps21 locus was mapped using 216 IBM RIL lines (Lee et al., 2002) and
further supported using select B73×Mo17 NILs (Eichten et al., 2011). Marker
data for the IBM RIL population were provided by Dr. Peter Balint-Kurti (USDA-ARS, Raleigh, NC). Windows QTL Cartographer (Version 2.5; http://statgen.ncsu.edu/~shchwang/WQTLCart.htm) was employed for metabolite Quantitative Trait Locus (mQTL) analysis with composite interval mapping (CIM). The WinQTLCart program was set as following: CIM program module=Model 6: Standard Model, walking speed=1 cM, control marker numbers=5, window size=10 cM, regression method=backward regression. Permutations (500) were run to determine the $P < 0.05$ logarithm (base 10) of odds (LOD) significance threshold (Churchill and Doerge, 1994). A list of RILs and NILs used for mapping in this study are given in (Supplemental Table S2). In effort to confirm and potentially refine the position of the mQTL identified using CIM, association analyses were also conducted on the IBM RILs using the General Linear Model (GLM) in TASSEL 5.0 (Bradbury et al., 2007) and the Unified Mixed Linear Model (MLM) to effectively control for false positives arising from the differential population structure and familial relatedness present in diversity panels (Yu et al., 2006). Unlike diversity panels, differential population structure and familial relatedness are not typically significant features in biparental RIL panels and thus the GLM and MLM models were predicted to generate similar results in the IBM RIL association analyses. Geneotypic data from imputed IBM RIL SNP markers (July 2012 All Zea GBS final build; www.panzea.org) were used for association
analyses of root β-cotic acid levels in the intermated B73 × Mo17 (IBM) population. 173,984 SNP markers with < 20% missing genotypes and minor allele frequency (MAF) > 15% were used.

A metabolite based genome-wide association study (mGWAS) was conducted for elicited levels β-cotic acid as a trait in the Goodman diversity panel (Flint-Garcia et al., 2005) using the Unified MLM in TASSEL 5.0 (Yu et al., 2006; Bradbury et al., 2007). Final analyses were conducted with the R package GAPIT (Zhang et al., 2010; Lipka et al., 2012), which involves EMMA (executed by R package) and Compressed MLM (CMLM) population parameters previously determined (P3D) to identify genomic regions putatively associated with the trait.

GWAS analyses utilized a B73 Version 2 referenced HapMap consisting of 246,477 SNPs previously derived from an Illumina 50K array (Cook et al., 2012) and a genotyping by sequencing (GBS) strategy (Elshire et al., 2011) filtering less than 20% missing genotype data with minor allele frequencies (MAF) > 5% (Samayoa et al., 2015; Olukolu et al., 2016). The kinship matrix (K), estimated from 246,477 SNPs was used jointly with population structure (Q) to improve association analysis (VanRaden, 2008). All metabolite data were log$_2$ transformed prior to statistical analysis to improve normality. The Quantile-Quantile plots and Manhattan plots were constructed in the R package qqman (http://cran.r-project.org/web/packages/qqman) (Turner, 2014).

Identification and Quantification of Metabolites
Unless otherwise stated, all maize tissue samples were rinsed with water, frozen in liquid N₂, ground to a fine powder in a mortar and stored at -80°C for further analyses. For Vapor Phase Extraction (VPE) based sample preparation, 50 mg aliquots were first weighed, solvent extracted in bead homogenizer, and derivatized using trimethylsilyldiazomethane as previously described (Schmelz et al., 2004; Schmelz et al., 2011). GC-MS analysis was conducted using an Agilent 6890 Series gas chromatograph coupled to an Agilent 5973 mass selective detector (interface temp, 250°C; mass temp, 150°C; source temp, 230°C; electron energy, 70 eV). The GC was operated with a DB-35MS column (Agilent, Santa Clara, USA, 30 m x 0.25 mm x 0.25 μm). The sample was introduced as a splitless injection with an initial oven temperature of 45°C. The temperature was held for 2.25 min, then increased to 300°C with a gradient of 20°C min⁻¹, and held at 300°C for 5 min. GC/EI-MS based quantification of β-costic acid was based upon the slope of an external standard curve constructed from β-costic acid (Ark Pharm, #AK168379) spiked into 50 mg aliquots of frozen powdered untreated maize stem tissues which were then processed using VPE (Schmelz et al., 2004). In representative samples analyzed by GC/EI-MS, β-costol was identified based 99% EI match within the Robert P. Adams essential oil MS library (Allured Books). While not previously detected in maize, β-costol is an anticipated an intermediate in samples rich in both β-selinene and β-costic acid.

For headspace recovery of ZmTps21 enzyme products by solid phase micro-extraction (SPME), fibers containing 100 μm polydimethylsiloxane (SUPELCO, Belafonte, PA, USA) were placed into reaction vials for 60 min
incubations at 30°C and then introduced into the GC injector for the analyses of
the adsorbed reaction products. GC-MS analyses conducted on SPME samples
utilized a splitless injection, a DB-5MS column (Agilent, Santa Clara, USA, 30 m
x 0.25 mm x 0.25 µm) and an initial oven temperature of 80°C. The temperature
was held for 2 min, then increased to 240°C with a gradient of 7°C min⁻¹, and
further increased to 300°C with a gradient of 60°C min⁻¹ and a hold of 2 min.
Precise instrument settings of the Agilent 5973 mass selective detector were
identical to those stated above used for plant samples. For GC-MS analysis with
a cooler injector, the injector temperature was reduced from 240°C to 150°C.

Volatiles emitted from elicited stems and naturally challenged roots of field
grown plants were collected by passing purified air over the tissue samples at
600 ml min⁻¹ and trapped on inert filters containing 50 mg HayeSep® Q (80-100
µm mesh) polymer adsorbent (Sigma-Aldrich, St. Louis, MO, USA). Individual
samples were then eluted with 150 µl methylene chloride, and analyzed by GC
coupled with flame ionization detector (FID) as previously described (Schmelz et
al., 2001). β-selinene and related volatiles were quantified by GC-FID using the
slope of an external standard curve of (E)-β-farnesene. Select samples were
analyzed by GC/EI-MS to confirm individual peak identities of representative
replicates. This included the comparison of retention times with authentic
standards and by comparison of mass spectra with Wiley, National Institute of
Standards and Technology and the Adams libraries.

To ensure maximal independence of the second GWAS replicate that was
grown in the field, analytical conditions utilized LC-MS instead of GC-MS.
Reacted stem tissues were first ground to a fine powder with liquid N\textsubscript{2} and weighed out in 50 mg aliquots. Tissue samples were sequentially and additively bead homogenized in 1) 100 μl 1-propanol: acetonitrile: formic acid (1:1:0.01), 2) 250 μl acetonitrile: ethyl acetate (1:1), and 3) 100 μl of H\textsubscript{2}O. Each combined sample consisted of a co-miscible acidified solvent mixture of primarily 1-propanol: acetonitrile: ethyl acetate: water in the approximate proportion of 11:39:28:22 which was then centrifuged at 15,000 rpm for 20 min. Approximately 150 μl the particulate free supernatant was carefully removed for LC/MS automated sample analyses utilizing 5 μl injections. The LC consisted of an Agilent 1260 Infinitely series HiP Degasser (G4225A), 1260 binary pump (G1312B), and a 1260 autosampler (G1329B). The binary gradient mobile phase consisted of 0.1% formic acid in H\textsubscript{2}O (solvent A) and 0.1% formic acid in MeOH (solvent B). Analytical samples were chromatographically separated on a Zorbax Eclipse Plus C18 Rapid Resolution HD column (Agilent: 1.8 μm, 2.1 x 50 mm) using a 0.35 ml min\textsuperscript{-1} flow rate. The mobile phase gradient was: 0–2 min, 5% B constant ratio; 3 min, 24% B; 18 min, 98% B, 25 min, 98% B, and 26 min 5% B for column re-equilibration before the next injection. Eluted analytes underwent electrospray ionization (ESI) via an Agilent Jet Stream Source with thermal gradient focusing using the following parameters: nozzle voltage (500 V), N\textsubscript{2} nebulizing gas (flow 12 l min\textsuperscript{-1}, 55 psi, 225°C) and sheath gas (350°C, 12 l min\textsuperscript{-1}). The transfer inlet capillary was 3500V and both MS1 and MS2 heaters were at 100°C. Negative ionization [M-H]\textsuperscript{-} mode scans (0.1 amu steps, 2.25 cycles s\textsuperscript{-1}) from m/z 100 to 1000 were acquired. After considerable unsuccessful attempts to
optimize parameters required to obtain meaningful daughter ion fragments from

\( \beta \)-costic acid, analyses relied exclusively on the native parent \([M-H]\) ion \( m/z \) 233

and stable retention time of 16.65 min separated from established maize

zealexins. Quantification utilized an external standard curve of \( \beta \)-costic acid (Ark

Pharm, #AK168379, Libertyville, IL, USA) analyzed under identical conditions.

Controlled Maize Elicitation Assays

Controlled maize elicitation assays used 30-40 day old greenhouse plants grown

in 1-l plastic pots or in the case of the Goodman diversity panel (second

replicate) field grown plants. Plants in damage-related treatment groups were slit

in the center, spanning both sides of the stem, with a surgical scalpel that was

pulled 8–10 cm upward to create a parallel longitudinal incision. The treatment

spanned the upper nodes, internodes, and the most basal portion of unexpanded

leaves. All fungal spore inoculations (1 × 10^7 ml^-1) treatments were performed in

100 \( \mu l \) of \( H_2O \). For experiments involving stem elicitation with heat-killed

\textit{Fusarium} hyphae, crude material was homogenized in a Waring blender at

maximum speed for 3 min in the presence of additional \( H_2O \) at 20-30\% (WT/WT)

to create a thick smooth paste. Approximately 500 \( \mu l \) of crude elicitor was

introduced into each slit stem followed by sealing the site with clear plastic

packing tape to minimize desiccation of the treated stem tissues. For each

individual experiment details relating to specific tissues, biological replications

and harvest time points are noted in the figures and captions.
For the assay of plant responses to long-term western corn rootworm (WCR; *Diabrotica virgifera virgifera*) herbivory, seeds of an IBM line carrying a functional *ZmTps21* gene (IBM-RIL-0287) were grown in 946 ml DM32R cups (Dart Container Corporation, Mason, MI, USA) filled with greenhouse potting media and fertilized following Gassmann et al. (Gassmann et al., 2011). Seeds were planted 1 month prior to WCR inoculation and maintained at 23°C – 28°C in a greenhouse with supplemental daylight balanced illumination on a 16:8 (L:D) photoperiod. Plants were watered daily as needed to prevent saturated soil conditions. Inoculation and care of ≥V5-V6 stage (Abendroth, 2011) treated plants followed from Gassmann et al. (Gassmann et al., 2011). Cups were inoculated with n=10 neonate WCR larvae (obtained from USDA-ARS-NCARL; Brookings, SD, USA) and held in an incubator at 24°C with 40%-60% RH and watered sparingly as needed to minimize pot flooding. The experiment utilized 4 replicates per treatment. After 17 d, 1 g samples of insect attacked and healthy root tissues were collected from the plants, frozen on dry ice and stored for chemical analyses.

**Diabrotica Species Preference and Performance Assays**

For studies on preference and performance, WCR eggs and *Diabrotica balteata* (LeConte) eggs were obtained from USDA-ARS-NCARL (Brookings, SD, USA) and Syngenta (Syngenta Crop Protection AG, CHE), respectively. All larvae were reared on the roots of germinating maize seedlings until use. For both *Diabrotica* species, 3rd instar larvae were used for all experiments. The
performance of *D. virgifera* and *D. balteata* larvae was evaluated by placing one pre-weighed larva into individual solo cups (Bioserv, Newark, DE, USA) containing moist filter paper and a 60 mg crown root section from the B73 inbred. Crown roots were covered with 50 µL β-costic acid in EtOH: H₂O (15 %: 85 %) to create a final tissue concentration of 100 µg g⁻¹ FW. Control roots were similarly treated with 50 µL EtOH: H₂O (15 %: 85 %). Larval growth was determined after 48 h. The preference of the root herbivores given a choice between control and β-costic acid complemented roots was evaluated in 9 cm dia. petri dishes (Greiner Bio-One GmbH, Frickenhausen, DE). Root tissue treatments followed from the performance experiment. One root of each treatment was placed in the petri dishes. Five larvae were introduced in between the two root sections and larvae feeding behavior was recorded at 0.5, 1, 2, 3 and 4 h after start of the trials.

**RNA Isolation and qRT-PCR**

Total RNA was isolated with TRIzol (Invitrogen, Waltham, MA, USA) according to the manufacturer’s protocol. First-strand cDNA was synthesized with the RETROscript reverse transcriptase kit (Ambion, Waltham, MA, USA) using random decamer primers. qRT-PCR was performed using Power SYBR Green Master mix (Applied Biosystems, Waltham, MA, USA), and 250 nM primers on a Bio-Rad CFX96™ Real-Time PCR Detection System. Mean cycle threshold values of triplicate reactions were normalized to EF-1α (GenBank accession no. AF136829) (Huffaker et al., 2011). Fold-change calculations were performed
using the equation $2^{-\Delta \Delta CT}$ (Livak and Schmittgen, 2001). qRT-PCR primers used in the current study are listed (Supplemental Table S1)

**Isolation of ZmTps21 cDNA from Mo17**

Total RNA was isolated as described above and subjected to TURBO™ DNA-free™ treatment (Ambion) followed by total RNA purification with RNeasy® Mini protocol for RNA cleanup (Qiagen, Hilden, GR). Approximately 1 µg of an equally mixed RNA pool from Mo17 meristem tissues elicited with heat killed *Fusarium* hyphae collected at different time points (8, 24, 32, and 48 h) was used for the construction of 5'- or 3'-RACE cDNA library with SMARTer RACE 5'/3' Kit (Clontech, Mountain View, CA, USA) in accordance with the manufacturers’ protocol. The 5’-end of B73-Zmtps21 was used to design primers for PCR amplification of the Mo17 ZmTps21 gDNA. A DNA fragment, which was larger than the one from B73 on the agarose gel, was amplified using primers 5’-TGTGAACCAACAAAGCAAGGC-3’ and 5’-GAGCTCACCAATCATAGCCTC-3’ cloned and sequenced. Based on the conserved sequences between B73 and Mo17, primers were designed to amplify of the 3’ and 5’ ends via rapid amplification of cDNA ends (RACE) (Clontech) from 5'/3' cDNA libraries of *Fusarium* elicited meristems of Mo17. The complete cDNA sequence of the Mo17 functional ZmTps21 was amplified with the primers Mo17 ZmTPS21F (5’-ATGGGATGGTGATATTGCTGCCG-3’) and Mo17 ZmTps21R (5’-TCAGGCACACGGCTTGAGG-3’) from the Mo17 5’-RACE cDNA library. Primers used to amplify ZmTps21 genomic DNA from B73, W22, CML247 and other diverse inbred lines (Ki3, M37W, MS71, M162W, Ki11, Mo18W, HP301, TX303,
OH43, Oh7B, KY21, Mo17) are listed (Supplemental Table S1). Corresponding unpublished sequences were deposited in GenBank with following accession numbers (MF614104, MF614105, MF614106, MF614107, MF614108, MF614109, MF614110, MF614111, MF614112, MF614113, MF614114, MF614115).

Assay for Terpene Synthase Activity

The complete open reading frame of Mo17 ZmTps21 was amplified with the primers Mo17 ZmTps21-fwd (CACCATGGATGGTGATATTGCTGCCG) and Mo17 ZmTps21-rev (TCAGGCACACGGCTTGAGGAAC) and the resulting PCR fragment was cloned into the vector pET100/D-TOPO® (Invitrogen, Carlsbad, CA, USA). Sequencing of several clones revealed intact Mo17 ZmTps21 and two cloning artifacts with altered 3’ ends. For heterologous expression in E. coli, the plasmids were introduced into the strain BL21 Codon Plus (Invitrogen, Carlsbad, CA, USA). Expression was induced by addition of isopropyl-1-thio-D-galactopyranoside to a final concentration of 1 mM. The cells were collected by centrifugation at 4,000g for 6 min, and disrupted by a 4 × 30 sec treatment with a sonicator in chilled extraction buffer (50 mM MOPS, pH 7.0, with 5 mM MgCl₂, 5 mM sodium ascorbate, 0.5 mM PMSF, 5 mM dithiothreitol and 10% v/v glycerol). The cell fragments were removed by centrifugation at 14,000 g, and the supernatant was desalted into assay buffer (10 mM MOPS, pH 7.0, 1 mM dithiothreitol, 10% v/v glycerol) by passage through a Econopac 10DG column (BioRad, Hercules, CA, USA). Enzyme assays were performed in a Teflon®-
sealed, screw-capped 1 ml GC glass vial containing 50 μl of the bacterial extract and 50 μl assay buffer with 10 μM (E,E)-FPP and 10 mM MgCl₂. SPME fiber sample enrichment of adsorbed reaction products and analyses by GC/MS is detailed above in “Identification and Quantification of Metabolites”.

**Bioassays of in vitro and in vivo β-costic acid activity as an antifungal agent**

Maize antifungal assays using purified β-costic acid (Ark Pharm, #AK168379) were performed using the Clinical and Laboratory Standards Institute M38-A2 guidelines as previously detailed (Schmelz et al., 2011). In brief, a 96-well microtiter plate-based method using a Synergy4 (BioTech Instruments, Inc.) reader was used to monitor fungal growth at 30 °C in broth media through periodic measurements of changes in OD at 600 nm. Each well contained 200 μl of initial fungal inoculum (2.5 × 10⁴ conidia ml⁻¹) with 0.5 μl of either pure DMSO or DMSO containing dilutions of β-costic acid.

For the mature root infection assays with *Fusarium* pathogens, individual maize plants were greenhouse grown in separate 10-liter pots and supplemented with 14-14-14 Osmocote (Scotts Miracle-Gro) fertilizer. In effort to closely parallel our observations from mature field roots and minimize the invasiveness of belowground treatments, we limited our selection to large nodal roots (≥2mm dia.) containing 1st order lateral roots that were visually apparent and easily accessed following the temporary removal of the pot. Spanning a length of 8 cm,
at 1 cm intervals selected nodal roots were punctured with a blunt ended circular steel pin (0.6mm dia) creating a total of 9 punctures. Divided across the 9 wound sites per nodal root and depending on treatment, 100 µls of either H₂O or 1 × 10⁷ conida mL⁻¹ of either *F. verticillioides* (*F.v.*) or *F. graminearum* (*F.g.*) were applied. Treatments were limited to exposed roots growing along the outer-edge of the soil in close contact with the vertical wall of the plastic pot. Following treatments, plants were carefully placed back into the pots for 7 days. For each line grown, namely B73, m050, Mo17 and m065, 3 treatments and 4 replicates were performed (4*4*3 = 48 plants). For determination of the fungal biomass, inoculated and damaged roots were collected 7 days after fungal inoculation. Total genomic DNA was extracted from the infected roots and subjected to real time qPCR using the *F. graminearum*-specific primers for a deoxynivalenol mycotoxin biosynthetic gene (*FgTri6*) and *F. verticillioides* specific primers for a calmodulin (*FvVER1*) gene (Mule et al., 2004; Horevaj et al., 2011) (SI Appendix, Table S1). The amount of pathogen DNA relative to plant DNA was estimated by qRT-PCR. Plant DNA quantification utilized a conserved genomic sequence of *ZmTps21/Zmtps21* DNA shared between B73 and Mo17 using forward (gTps21-F, GCAGATGTGTTCGACAAGTTCC) and reverse (gTps21 R- TTACCTGCAGATTTCCTAAGCTCTC) primers with calculated amplification efficiencies of 102.65-102.89% between inbreds (Supplemental Table S1). Relative amounts of fungal DNA were calculated by the 2⁻^ΔΔCt method, normalized to a conserved genomic sequence of *ZmTps21/Zmtps21* DNA shared between B73 and Mo17.
**Statistical Analyses**

ANOVA were performed on the quantified levels of terpenoids, qRT-PCR transcripts, fungal growth and levels of fungal DNA. Treatment effects were investigated when the main effects of the ANOVAs were significant (P<0.05). Tukey tests were used to correct for multiple comparisons between control and treatment groups. The short-term preference and 2-d performance of *Diabrotica* larvae on roots, with and without additional β-costic acid, were analyzed with one sample t-tests and two-way ANOVA using SigmaPlot 13.0 (Systat Software Inc, San Jose, CA, USA), respectively.

**Supplemental Materials**

**Figure S1.** α/β-selinene derived oxidative products, β-costol, β-costal, α-costic acid and β-costic acid coexist as a network of maize metabolites.

**Figure S2.** Replicated and comparative association analyses confirm detection of *ZmTps21* as a gene candidate involved in β-costic acid biosynthesis.

**Figure S3.** Confirmation of the locus identified by combined linkage and association mapping based on β-costic acid levels using B73 and Mo17 near isogenic lines (NILs).

**Figure S4.** Sequence comparison of Mo17 ZmTps21 with other plant terpene synthases known to catalyze the protonation of neutral reaction intermediates.

**Fig. S5.** *ZmTps21* gene structure and sequence polymorphisms across numerous diverse inbred lines support the occurrence of a common and conserved B73-like mutation.
**Figure S6.** Deduced amino acid sequence comparison of ZmTps21 across select maize inbred lines.

**Figure S7.** C-terminal modifications in Mo17 ZmTps21 support an influential role in the protonation of germacrene A as putative reaction intermediate.

**Figure S8.** Germacrene A is minor yet detectable product of Mo17 ZmTps21 and is converted to β-elemene during GC injection at 240°C.

**Figure S9.** ZmTps21 derived products inhibit fungal growth at physiologically relevant concentrations *in vitro* and can be assessed *in vivo* using IBM near isogenic lines (NILs).

**Table S1.** Primers used for qRT-PCR analysis and sequencing ZmTps21 genomic DNA

**Table S2.** Maize lines specifically used to identify ZmTps21

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**Figure Legends**

**Figure 1.** β-selinene and β-costic acid can occur as major components of maize roots in field grown plants. Visibly (A) infected or (B) healthy field collected sweet corn (var. Golden Queen) root samples following trimethylsilyldiazomethane derivatization of carboxylic acids to corresponding methyl esters. Labeled peaks in representative GC/EI-MS total ion chromatograms (TIC) include: 1, β-selinene; 2, α-selinene (shoulder); 3, β-costic acid; 4, zealexin A1; and 5, zealexin B1. The presence of common fatty acids, namely palmitic acid and steric acid, are unchanged in healthy root tissues and directly labeled for reference. Corresponding EI spectra (m/z) of (C) β-selinene, (D) α-selinene, and (E) β-costic acid methyl ester from maize field collected roots. (F) Proposed α/β-costic acid biosynthetic pathway in maize starting from farnesyl diphosphate (FPP).

**Figure 2.** β-selinene can exist as a dominant elicited volatile and the pathway product β-costic acid can reduce herbivore performance. Representative GC-FID traces of volatile emissions collected from live roots of field grown maize lines (A) B73, (B) Mo17 and (C) IBM-RIL 0287 20 days after pollination. (D) Average (n = 4, ± SEM) quantity (µg 12 h⁻¹ g⁻¹ DW) of β-selinene volatiles emitted from respective maize roots. Representative GC-FID traces of emitted volatiles collected from living (E) control B73, (F) C. heterostrophus-infected B73, (G) control Mo17 and (H) Mo17 C. heterostrophus-infected stems. (I) Average (n = 4, ± SEM) quantity (ng cm⁻² h⁻¹) of β-selinene emitted as a volatile from the stems of 5-week-old plants following damage and treatment with H₂O (Dam) or with 100 µl of 1 x 10⁷ spores C. heterostrophus (C.h.). Within plots D and I, different letters (a–c) represent significant differences (All ANOVA Ps < 0.05; Tukey test corrections for multiple comparisons: P < 0.05). (J) Average (n = 4, ± SEM) root tissue concentrations (µg g⁻¹ FW) of β-selinene and β-costic acid levels in the roots of IBM-RIL-0287 following 17 days of either no treatment (Ctr) or herbivory by western corn rootworm (WCR) (Diabrotica virgifera virgifera) larvae (Student’s t-test; one-tailed distribution, equal variance). (K) Average WCR (n = 18, ± SEM) and Diabrotica balteata (n = 57, ± SEM) preference over 4 h for excised maize roots treated with either EtOH:H₂O (15:85) alone (Control) or the same solution containing β-costic acid to achieve a root tissue concentration of 100 µg g⁻¹ FW. Each replicate (n) consisted of assays with 5 individual 3rd instar larvae where distributions were measured at 30,60, 90, 120, 180, 240 min and collectively averaged (one sample t-test, Ps > 0.05). (L) Average (n ≥ 5, ± SEM) performance (% relative weight gain) of 3rd instar WCR and D. balteata larvae over 2 days of feeding on root tissues with (+) and without (-) additions of β-costic acid as described in the preference study (two-way ANOVA P < 0.05).
Figure 3. Combined linkage and association mapping identifies ZmTps21 as a candidate β-selinene synthase. (A) Major mQTL for β-costic acid production detected on chromosome 9 by composite interval mapping (CIM) using IBM recombinant inbred lines (RILs). (A-insert) Comparative association analysis of the IBM-RIL β-costic acid levels using the General Linear Model (GLM) and 173,984 SNPs. The most statistically significant SNP is located at 127,854,265 on Chromosome 9 (B73 RefGen_v2) with a dashed line denoting the 5% Bonferroni correction. (B) Quantile-quantile plot for association analysis of β-costic acid levels in the Goodman diversity panel. (C) Manhattan plot of the association analysis (MLM) of β-costic acid levels in replicate 1 of the Goodman diversity panel following 3 days of fungal elicitation. Dashed line denotes the 5% bonferroni-corrected threshold for 246,477 SNP markers with the most statistically significant SNP located at 127,858,963 (B73 RefGen_v2) on Chromosome 9. (D) Location of the candidate gene ZmTps21 on the physical map supported by both linkage analysis and association analysis. (E) Fine-mapping with IBM near-isogenic lines (NILs); B73 and Mo17 chromosomal segments are represented by blue and red, respectively. β-costic acid chemotypes of IBM-NILs are indicated as GC/El-MS traces (m/z = 233). (F) Agarose gel PCR amplified products demonstrate a cDNA length polymorphism between B73 Zmtps21 and Mo17 ZmTps21 candidates. (G) Diagrammatic structures of B73 Zmtps21 and Mo17 ZmTps21 genes based on sequencing. Exons and introns are denoted as rectangular bars and as black lines, respectively. Open rectangle indicates the missing B73 genomic DNA and relative position of encoded conserved RXR and DDXXD motifs terpene cyclase activity.

Figure 4. Mo17 ZmTps21 encodes a functional β-selinene synthase. (A) Mo17 ZmTps21 was in Escherichia coli and the resulting protein extract was incubated with (E,E)-farnesyl diphosphate (FPP). Mo17 ZmTps21 products were collected using solid-phase microextraction and analyzed by GC/MS revealing (2) β-selinene as the dominant product with lower yet detectable levels of (1) β-elemene (germacrene A rearrangement product) and (3) α-selinene. (B) Celery fruit essential oil was used as a natural product standard for β-selinene/α-selinene (9:1).
Figure 5. ZmTps21 transcripts are elicited by diverse fungi and precede β-costaic acid accumulation detectable in diverse maize lines. Average (n = 4; ±SEM) Mo17 (A) ZmTps21 (B) β-costaic acid (C), ZmTps6/11 and (D) zealexin A1 as qRT-PCR fold changes of transcripts and corresponding phytoalexin concentrations (µg g⁻¹ FW) in intact control stems (Con) or those damaged and treated with either H₂O (Dam), or a heat-killed Fusarium elicitor (F.E.) hyphae preparation after 1, 2, or 4 days. Average (n = 4; ±SEM) Mo17 (E) ZmTps21 (F) β-costaic acid (G), ZmTps6/11 and (H) zealexin A1 as qRT-PCR fold changes of transcripts and corresponding phytoalexin concentrations (µg g⁻¹ FW) in intact control stems (Con) or those damaged and treated with either 100 µl of H₂O (Dam) alone or spore suspensions (1×10⁷ ml⁻¹) of R. microsporus (R.m.), A. parasiticus nor-1 (A.p.), F. verticillioides (F.v.), or C. heterostrophus (C.h.) and harvested at 2 and 4 days for transcripts and metabolites, respectively. (I) Average (n = 4, ± SEM) β-costaic acid concentrations (µg g⁻¹ FW) in the scutella of 10-old maize seedlings from 15 inbred maize lines and mature field collected roots displaying necrosis. Hybrids include sweet corn (var. Golden Queen; GQ) and IBM-RIL0287. Within plots, different letters (a-e) represent significant differences (all ANOVA P < 0.05; Tukey test corrections for multiple comparisons: P < 0.05).

Figure 6. ZmTps21 derived products inhibit Fusarium fungi in vitro and correspond with improved disease resistance in vivo. Average (n = 8, ± SEM) fungal growth estimates (600 nm OD) of (A) F. verticillioides, and (B) F. graminearum, in liquid media in the presence of β-costaic acid at 0 (○), 25 (●), and 100 (∆) µg ml⁻¹. Average (n = 4, ± SEM) ratio of fungal DNA / plant DNA levels present in maize roots 7 days after damage and inoculation with 100 µls of either H₂O or 1 × 10⁷ conida mL⁻¹ of (C) F. verticillioides and (D) F. graminearum in B73, Mo17 and IBM-NILs harboring active (+; m065) and inactive (-; m050) alleles of ZmTps21. Within plots, different letters (a–c) represent significant differences (All ANOVA P < 0.05; Tukey test corrections for multiple comparisons: P < 0.05).
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Parsed Citations


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