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Maize resistance to witchweed through changes in strigolactone biosynthesis


Maize (Zea mays) is a major staple crop in Africa, where its yield and the livelihood of millions are compromised by the parasitic weed Striga. Germination of Striga is induced by strigolactones exuded from maize roots into the rhizosphere. In a maize germplasm collection, we identified two strigolactones, zealactol and zealactonoic acid, which stimulate less germination than the major maize strigolactone, zealandol. We then showed that a single cytochrome P450, ZmCYP706C37, catalyzes a series of oxidative steps in the maize-strigolactone biosynthetic pathway. Reduction in activity of this enzyme and two others involved in the pathway, ZmMAX1b and ZmCLAM1, can change strigolactone composition and reduce Striga germination and infection. These results offer prospects for breeding Striga-resistant maize.

Food security is a growing challenge in the face of climate change and increasing food needs (1). Maize (Zea mays) is one of the most important staple crops in the world, especially in Africa. There, its yield is compromised by the parasitic weeds Striga hermonthica and Striga asiatica. Damage from these Striga species threatens the livelihood of millions of people, particularly in sub-Saharan regions (fig. S1) (2, 3). Striga seeds lay dormant in soil until their germination is triggered by strigolactones (SLs), signaling compounds exuded by the roots of plants, including maize. The first known SL, strigol, was discovered in the 1960s in the root exudates of cotton (4). In addition to having been co-opted as a cue for root-paraitic plants, SLs serve as host signals for beneficial arbuscular mycorrhizal fungi (AMF) and are plant hormones with developmental roles (5–9).

Thus far, more than 35 different SLs have been discovered, all containing the conserved A-ring (Fig. 1A) (10–12). The canonical SLs include two groups, the “strigol-type” and “orobanchol-type,” whereas noncanonical SLs lack the A-, B-, and/or C-rings (10–12). Plants usually exude a blend of different SLs, and the composition of the root exudate can vary greatly between and sometimes also within plant species. Many of the SLs display substantial differences in their biological activity, such as the induction of AMF hyphal branching and parasitic plant germination (9, 13–15). The biological importance of SL blends is far from understood, but in sorghum (Sorghum bicolor), a change in SLs from 5-deoxyzealacton to orobanchol decreased Striga germination and increased field resistance (16).

The mechanisms of SL biosynthesis have only been partially elucidated. Three enzymes—DWARF 27 (D27) and two carotenoid cleavage dioxygenases (CCDs), CCD7 and CCD8—catalyze the conversion of β-carotene to carlactone (CL) (Fig. 1A) (17, 18). In Arabidopsis, CL is oxidized to form carlactonoic acid (CLA) (Fig. 1B) (17, 18). Arabidopsis has two copies of this MAXI, whereas maize has three homologs, and rice has five (18, 20). Although both the Arabidopsis AtMAXI and the maize ZmMAX1b form CLA from CL, the rice MAXI homologs, Os900 and Os1400, instead convert CL to 4-deoxyorobanchol (4DO) and orobanchol, respectively (18, 21). Dicots also form orobanchol, but from CLA rather than CL, and with a different cytochrome P450, CYP722C. A homolog of this CYP722C can also produce 5-deoxyzealactol from CLA (22, 23).

Maize roots exude at least six SLs, two of which have been structurally identified as zealactone and zeapyranolactone (Fig. 1A) (24–26). However, the identities of the other four SLs remained elusive, as well as the biosynthetic differences between the six and their individual roles in Striga germination. In this study, we reveal natural variation in the maize SL blend, identify three new maize SLs, elucidate the entire maize SL biosynthetic pathway, and show that changes in the composition of the SL blend correspond to differences in Striga germination and infection. These findings create a pathway for reducing the notorious agricultural problem of Striga infection through breeding maize for favorable SL composition.

Natural variation in strigolactone production by maize

To assess the extent of variation in the production of SLs by maize, we grew a collection of maize genotypes, sampled their root exudate, and analyzed SLs with multiple reaction monitoring (MRM) liquid chromatography–tandem mass spectroscopy (LC/MS/MS) (Fig. 1B and figs. S2 and S3) (24, 25). Quantities of exuded SLs varied among these lines (Fig. 1B and fig. S3). Moreover, one of the genotypes, NP2222, displayed a distinctive SL profile, lacking detectable levels of all but two SLs, an unknown SL and designated compound 5 (Fig. 1B and fig. S3). Compound 5 was previously noted in maize root exudate (24), but its low abundance and chemical instability hampered structural characterization. Therefore, on the basis of nuclear magnetic resonance (NMR) spectra and retrosynthetic analysis (24, 27–29), we postulated structures and subsequently synthesized compound 5 as well as the other unknown SL (figs. S4 to S12). The synthetic products were identical to the natural ones in maize root exudate and were designated zealamol (compound 5) and zealactonoic acid (ZA) (the other unknown SL) (figs. S9 and S12).

Bioassay of Striga germination showed that both zealamol and ZA were less inductive than zealandol (Fig. 1C), an outcome that highlights how strongly minute differences in SL structure can alter their biological activity. These findings are further supported by work on sorghum (16). To unravel the mechanistic basis for these differences in SL blends, we revealed the biosynthetic pathway of maize SLs.

Three maize genes encode the carlactone biosynthetic pathway

Through homology, we identified the maize orthologs D27, CCD7, and CCD8, which catalyze the formation of CL from β-carotene in other plant species (tables S1 and S2). To confirm ZmCCD8 function, we analyzed root exudate of two independent zmccd8 mutants (in W22 and Mo17 backgrounds) (30). Zealactone was not detected, although it was the major SL in
wild-type exudate (fig. S13A), showing that ZmCCD8 is a key enzyme in maize SL biosynthesis (17, 31, 32). The transient expression of ZmD27 (GRMZM2G158175), ZmCCD7 (GRMZM2G158657), and ZmCCD8 (GRMZM2G446858) together in Nicotiana benthamiana led to accumulation of CL (Figs. 1A and 2A, fig. S14A, and table S3), which is consistent with results from rice and tomato orthologs (21, 33).

Identification of gene candidates for carlactone conversion

On the basis of the structures of the maize SLs identified thus far (Fig. 1A and fig. S2) (24–26), we postulated the involvement of a methyl transferase and several CYPs in the pathway downstream of CL. Several bioinformatic approaches were combined to select candidate genes for further functional characterization.

Mutual Rank (MR)–based global gene coexpression analysis (34, 35) showed that of the three maize MAX homologs, only ZmMAXib tightly coexpressed with ZmCCD8 (fig. S15), making it the strongest candidate for the next biosynthetic step. Analysis of root exudate from a zmmaxa1 zmmaxc1 double mutant (supplementary materials) showed wild-type levels of zealactone, thus excluding both homologs from being the biosynthetic genes we sought (fig. S13B). Earlier research also demonstrated that ZmMAXib (GRMZM2G023952) converts CL to CLA more efficiently than does ZmMAXia (GRMZM2G108612) or ZmMAXic (GRMZM2G070508) (18). The amounts of CL in leaf extracts decreased after cofiltration with ZmMAXib with ZmD27, ZmCCD7, and ZmCCD8 in N. benthamiana, (Fig. 2A), confirming that ZmMAXib uses CL as a substrate (18). However, only traces of the expected product, CLA, were detected in this expression system (Fig. 2B and fig. S14B). To resolve this enigma, N. benthamiana extracts were analyzed with LC–quadrupole time-of-flight (QTOF)–MS. Prominent peaks of CLA-hexose and CLA-dihexose conjugates were detected in samples expressing the maize CL pathway genes together with ZmMAXib. These conjugates were lacking in control samples and other gene combinations (Fig. 2C and table S4). Similar conjugation has been demonstrated for the transient production of other acidic compounds with N. benthamiana (36, 37).

For selection of remaining candidate genes, we combined three approaches: (i) MR–based coexpression with ZmCCD8 and ZmMAXib as baits (fig. S15), (ii) coexpression modules in MaizeGGM2016 (38), and (iii) differential gene expression in a zmccd8 mutant (Fig. 2D). For the latter, we assumed that SL pathway genes downstream of CCD8 would be transcriptionally regulated in the zmccd8 mutant (39). The ZmCCD7, ZmCCD8, and ZmMAXib genes clustered together in MaizeGGM2016 module 091, suggesting that the 32 other genes in this module were candidates for the missing pathway genes (table S5). In the roots of zmccd8 seedlings, 1301 genes were differentially expressed (DEGs) (less than or equal to twofold change, false discovery rate (FDR) < 0.05) compared with the B73 wild type (tables S5 and S6). These three approaches shared a seven-gene overlap (Fig. 2D and table S2) in which three GRMZM2G033126, GRMZM2G158342, and GRMZM2G023952 (ZmMAXib) formed a putative gene cluster on chromosome 3 (Fig. 2, D and E, and fig. S15) (39). Genes homologous to these also cluster in other Poaceae species (fig. S16), but the functional importance is unknown. So too is the identity of SLs produced by some of these species, such as switchgrass.

ZmCLAMT1 is a carlactonic acid methyltransferase

Because SLs zealactone and zeapyranolactone are methyl esters, their proposed precursor has been methyl carlactonoate (MeCLA) (24). Thus, we sought a methyltransferase gene that causes the formation of MeCLA from CLA. We bioinformatically identified a top candidate (GRMZM2G033126) (Fig. 2, D and E), which
Fig. 2. Identification of gene candidates for maize strigolactone biosynthesis. (A and B) Representative MRM-LC/MS/MS chromatograms of carlactone (CL), [M+H]^+/m/z 303 > 97 (A), and carlactonic acid (CLA), [M-H]/m/z 331 > 113 (B), in N. benthamiana leaf samples transiently expressing maize strigolactone (SL) precursor pathway genes. (C) Untargeted metabolomics to identify CLA conjugates in N. benthamiana leaf samples. m/z 539.21: CLA + hexose + formic acid ~ H2O; m/z 701.26: CL + 2 hexose + formic acid ~ H2O (D) Venn diagram of candidate gene numbers from several analyses: module091 from maizeGGM, genes differentially expressed from several analyses: module091 from maizeGGM, genes differentially expressed from several analyses: module091 from maizeGGM, genes differentially expressed from several analyses: module091 from maizeGGM.

ZmCYP706C37 catalyzes formation of several maize strigolactones

The other candidate genes were coinfiliated by different combinations of precursor-pathway genes. Coinfiltration of ZmCYP706C37 (GRMZM2G158342) (42) by those encoding the MeCLA pathway decreased levels of MeCLA, indicating that this CYP can use MeCLA as a substrate (fig. S17A) and produce zealcate (Fig. 3A and fig. S2). To check for possible biosynthetic pathways, we also coexpressed ZmCYP706C37 with genes encoding the CL pathway enzymes. This combination resulted in production of zealcate (Fig. 4A and fig. S17B).

Formation of both zealcate and zealcactol involves complex rearrangement of the SL ring and, for zealcactol, a hydroylation at C19 as well. To exclude the possibility of endogenous enzymes from N. benthamiana contributing to these complex conversions, we expressed ZmCYP706C37 in yeast, isolated its microsomes, and analyzed product formation with different substrates (Figs. 3B and 4B). This approach confirmed that ZmCYP706C37 can convert MeCLA to zealcactol and CL to zealactol (Fig. 1A).

For additional insight into the parallel biosynthetic pathway of CL to zealactol, we further analyzed samples from N. benthamiana and yeast microsome assays with untargeted metabolomics and MRM-LC/MS/MS. This process revealed another putative intermediate, 3-oxo-19-hydroxy-CL (compound 7) (Fig. 1A and 3C). We used them here as substrates in our ZmCYP706C37 expressing yeast-microsome assay, and both were successfully converted to zealactone (Fig. 3D). We developed an MRM method for detection of these compounds (fig. S2) and identified them as intermediate products in the conversion of MeCLA to zealactone (fig. S18). Moreover, analysis of maize root exudate revealed that 3-oxo-MeCLA is also a natural maize SL previously referred to as compound 6 (fig. S19 and Fig. 1A) (24). These results demonstrate that a single enzyme, ZmCYP706C37, can catalyze the many oxidative steps necessary for the conversion of MeCLA to zealactol that were previously hypothesized to require several enzymes (Figs. 1A and 3C) (24).

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Moreover, agroinfiltration of the CL pathway genes with ZmCYP706C37 and ZmMAX1b resulted in production of ZA, a result also confirmed with LC-QTOF-MS (Fig. 4, C and D, and fig. S22).

Last, analysis of root exudate from a zmcyp706c37 mutant [EMS4-045ad8, stop-codon gained (fig. S23A)] showed no detectable levels of zealactol, ZA, zealactone, or three other SLs derived from the latter (fig. S23B) (44). Although 3-oxo-MeCLA was detectable in the mutant exudate, it was present at a much lower level than in that of the wild type. Instead, CLA and MeCLA accumulated in the mutant exudate, whereas they are absent in the wild type exudate (fig. S23, C and D). Together, these data support our functional characterization of ZmCYP706C37.

**Biosynthetic control of the maize strigolactone blend**

To determine how the different maize SLs are biosynthetically related, we applied 3-hydroxy-MeCLA, 3-oxo-MeCLA, and zealactol to seedlings...
of another commercial line, NK Falkone, which were treated with fluridone, an inhibitor of SL biosynthesis (45). Each of these three compounds complemented zealactone production (fig. S24A), confirming that they can serve as biosynthetic precursors for zealactone. Combined transient expression of ZmMAX1b and ZmCLAMT1 in N. benthamiana leaves and subsequent infiltration of zealactol also showed that the latter can be converted to zealactone by ZmMAX1b together with ZmCLAMT1 (Fig. 1A and fig. S25). Application of zealactone to fluridone-treated plants led to the formation of zeapyranolactone and two other maize SLs, designated compounds 3 and 4, suggesting that zealactone is their precursor (Fig. 1A and fig. S24, B to D) (24).

Next, we sought mechanisms underlying the distinctive maize SL profile of NP2222 (fig. S26). This line produces zealactone in fluridone-treated seedlings, as does NK Falkone, but only from MeCLA and 3-oxo-MeCLA, not from zealactol (figs. S24A and S26A), suggesting inactivity of MAX1b and/or CLAMT1. As previously noted, ZA accumulated in the root exudate of NP2222 (Fig. 1B and fig. S26D), indicating dysfunction of CLAMT1. Zealactol added to either NK Falkone or NP2222 was converted to ZA, showing that ZmMAX1b is active in NP2222 (fig. S26, B and C). Inspection of the CLAMT1 sequence in a proprietary NP2222 genome database revealed a large insertion in the second exon of this gene, and reverse transcriptase polymerase chain reaction (RT-PCR) showed that regions flanking the insertion were not transcribed (fig. S26E). These collective data indicate disfunction of CLAMT1 in NP2222.

To analyze biological consequences of the different SL profiles, several maize lines were selected for Striga germination and infection assays. The NP2222 root exudate induced much lower germination than that of NK Falkone. Results were consistent with their respective SL profiles and differences in germination-inducing activity of the individual SLs (Figs. 1C and 5A and fig. S26D). CML52 and NC358, both with high proportions of zealactol and ZA, induced significantly less Striga germination than did CML69 and Ky21, which produced mostly zealactone despite similar total SL peak areas (Figs. 1C and 5A, and fig. S27, A and B). These differences were also reflected in a Striga infection assay with a containerized system, in which Striga emergence was less for low-zealactone genotypes (Fig. 5B). In addition to their SL blend, these lines may have other genetic differences that could affect these results. However, we also analyzed a gene-suppression mutant of ZmMAX1b (transposon insertion in a W22 background) (fig S28, A and B). This mutant exuded significantly less isozearactone and zeapyranolactone-derived SLs, whereas the level of zealactol was higher than in the W22 control (Fig. 5C). The zmmx1b mutant also induced less Striga germination and emergence (Fig. 5E). Results confirm that a change in activity of specific SL biosynthetic enzymes in maize can change the SL composition and confer Striga resistance. Although the underlying mechanisms are completely different, these findings resemble those of lgs sorghum (16) and present a promising prospect for Striga resistance breeding in maize. The zmmx1b mutant did not exhibit a branching phenotype, in contrast to zmcd8 (fig. S28C). Also, zmcdp706c37, which is located parallel to or downstream of ZmMAX1b, did not display an obvious branching phenotype either. This all suggests that the downstream SLs are not nor precursors of the branching inhibiting hormone and are therefore safe breeding targets that will not result in unwanted pleiotropic effects.

Conclusions

We have shown that two parallel SL biosynthetic pathways operate in maize and that both pathways produce the major maize SL, zealactone. Changes in flux through these pathways can alter the maize SL profile by shifting the balance between zealactone and zealactol.
plus ZA. Zealactol and ZA induce much less *Striga* germination, thus imparting a strong reduction in *Striga* infection to genotypes that exude more zealactol and ZA than zealactone. Future research should investigate whether these changes in the SL blend affect colonization by AM fungi, which was not observed for *Igs* sorghum (16). Our results offer a perspective for breeding *Striga* resistance through modification of the SL blend in maize and thus potentially reducing the devastating effects of this parasitic weed in Africa.

REFERENCES AND NOTES


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Competing interests: M.H.M. is a consultant to Corteva Agriscience, but that company was not involved in this work. All the other authors declare that they have no competing interests.

Data and materials availability: The maize mutants zmccd8 and zmmaxAzmjmaxxc1 were obtained via a material transfer agreement (MTA) with the University of Florida Board of Trustees. The RNA-seq data of zmccd8 and 873 root tissues are available in the NCBI database (BioProject PRJNA757767) under accession numbers SRR15613590, SRR15613591, SRR15613599, SRR15613593, SRR15613594, and SRR15613595. All the other data are presented in the main text and in the Supplementary Materials. License information: Copyright © 2023 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. https://www.science.org/about/science-licenses-journal-article-reuse

SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S28

Tables S1 to S8

References (46–70)

View/request a protocol for this paper from Bio-protocol.

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