Unlinked genetic loci control the reduced transcription of aminopeptidase N 1 and 3 in the European corn borer and determine tolerance to Bacillus thuringiensis Cry1Ab toxin

Brad S. Coates a,b,*, Douglas V. Sumerford a,1, Blair D. Siegfried c, Richard L. Hellmich a,b, Craig A. Abel a

a USDA-ARS, Corn Insect and Crop Genetics Research Unit, Genetics Laboratory, Iowa State University, Ames, IA 50011, USA
b Department of Entomology, Iowa State University, Ames, IA 50011, USA
c USDA-ARS, Corn Insect and Crop Genetics Research Unit, Genetics Laboratory, Iowa State University, Ames, IA 50011, USA

A R T I C L E   I N F O

Article history:
Received 21 August 2013
Received in revised form 3 September 2013
Accepted 16 September 2013

Keywords:
Crystalline (cry) toxin resistance
Gene network
Gene regulation

A B S T R A C T

Transgenic expression of Bacillus thuringiensis (Bt) crystalline (Cry) toxins by crop plants result in reduced insect feeding damage, but sustainability is threatened by the development of resistance traits in target insect populations. We investigated Bt toxin resistance trait in a laboratory colony of the European corn borer, Ostrinia nubilalis, selected for increased survival when exposed to Cry1Ab and correlated survival on Cry1Ab toxin with a constitutive \(146.2 \pm 17.3\)-fold reduction in midgut aminopeptidase N1 (apn1) transcript levels. A \(7.1 \pm 1.9\)-fold reduction apn3 transcript level was also correlated with Cry1Ab resistance. Quantitative trait locus (QTL) mapping identified a single major genome region controlling Cry1Ab resistance on linkage group 24 (LG24), and a minor QTL on LG27. Both QTL were independent of apn1 and apn3 loci on LG02. Positional mapping identified genetic markers that may assist in the identification of causal gene(s) within QTL intervals. This study indicates that genetic factor(s) may act in trans to reduce both apn1 and apn3 expression in Cry1Ab resistant O. nubilalis larvae, and suggest that gene regulatory pathways can influence Bt resistance traits. These findings show that gene interactions (epistasis) may influence Bt resistance in target insect populations.

1. Introduction

The transgenic expression of crystalline (cry) protein toxins derived from the soil bacterium Bacillus thuringiensis (Bt) by crop plants are a success story for biotechnology. Genetically engineered (GE) plants that express Bt toxins can dramatically reduce feeding damage caused by target insects, and have likely been a cause of decreased pest insect population sizes and levels of crop damage (Hutchison et al., 2010). These benefits have contributed to a high rate of GE crop adoption by producers, such that by 2010 GE corn comprised \(63\%\) of the 35.6 million hectares planted in the United States (USDA-NASS 2010). Continual exposure of insect populations to high levels of a insecticide can lead to the selection of tolerant or resistant phenotypes (Labbé et al., 2007), and the potential for resistance development has been a concern since the commercialization of Bt crops in the late 1990s. Resistance was first documented in the lepidopteran insect species Plodia interpunctella (McGaughy, 1985), Plutella xylostella (Tabashnik et al., 1990), and Tricoplusia ni (Janmaat and Myers, 2003) in response to selection caused by applications of foliar Bt sprays. Initial description of resistance traits and subsequent modeling of potentials for accumulation of resistance phenotypes in pest insect populations were based on what is referred to as “Mode 1” Bt resistance. “Mode 1” resistance traits in Lepidoptera are defined a being recessive, showing \(>500\)-fold increases in resistance compared to wildtype individuals, having negligible cross-resistance to Cry1C and showing reduced binding of Cry1A toxins to midgut epithelium due to action of a single gene (Tabashnik et al., 1998).
Insect resistance management programs aimed to delay the accumulation of Bt resistance traits in pest insect populations have used the high-dose/refuge (HDR) strategy (Alstad and Andow, 1995; US EPA, 2001). A “high dose” of Bt toxin is hypothesized to cause mortality among 100% of homozgyous susceptible and heterozygous larvae that feed on the GE crop plant. In conjunction with a “high dose”, the HDR strategy relies on planting of non-Bt (conventional) crop plants that functions as a repository where an excess of susceptible phenotypes will develop to adulthood. When refuges are planted in proximity to Bt fields, a large number of susceptible individuals are likely to mate at random with rare homozygous resistant adults that might emerge from Bt fields. Mode 1 resistance forms the premise behind the HDR strategy that is used for insect resistance management of Bt resistance in populations of pest insects (US EPA, 2001). Despite of required implementation of IRM programs for Bt product registrations, field-evolved resistance to transgenic Bt cotton expressing the Cry1Ab toxin has been shown in populations of *Bunseola fusca* (van Rensburg, 2007) as well as Bt hybrids that express Cry1F toxin by *Spodoptera frugiperda* (Matten et al., 2008). Additionally, cotton bollworm populations show resistance to Cry1Ac-producing cotton in India (Kranthi, 2005; Chintala et al., 2007), and the southern United States (Tabashnik et al., 2008). Although not detected in field settings, a field-derived laboratory colony of *Ostrinia nubilalis* is known to survive and develop on corn hybrids that express Cry1F toxin (Pereira et al., 2008).

The molecular genetic basis of “Mode 1” Bt resistance has been shown to result from structural mutations in insect receptor proteins (Gahan et al., 2001, 2010) or a reduced expression of a single toxin receptor gene (Zhang et al., 2009; Herrero et al., 2005; Tiewsiri and Wang, 2011). For example, aminopeptidase N (apn) genes expressed in the midgut encode epithelial membrane-bound enzymes that are also bound by Cry1Aa, Cry1Ab, and Cry1Ac (Chang et al., 2008; Zhang et al., 2009), as well as Cry1F (Hua et al., 2001) and Cry1C toxins (Herrero et al., 2005). Reduced expression of *apn1* transcripts was shown to eliminate Cry1C binding to *Spodoptera exigua* brush border membrane vesicles and was correlated with larval resistance to Cry1C (Herrero et al., 2005). Additional single gene Bt resistance traits were shown to result from mutations in the midgut epithelial membrane-anchored proteins ABC transporter (*abc*c), alkaline phosphatase (*alp*), or cadherin (*cad*) (Gahan et al., 2001, 2010; Jurat-Fuentes et al., 2002; Baxter et al., 2011) of larval Lepidoptera. Cry1Ac resistance in the YHD2 strain of *Heliothis virescens* was shown to involve mutations in both *cad* and *abc*c genes (Gahan et al., 2001, 2010). Despite this knowledge, the genetic basis of Bt resistance remains difficult to discern in many cases, where Baxter et al. (2008) and Coates et al. (2011a,b) also reported that Cry1 toxin resistance traits are conferred by loci that do not include genes that are known to encode proteins which are bound by Bt toxins.

Complexities of the molecular mechanisms involved in the expression of “Mode 1” resistance in Lepidoptera was shown by characterization of genetic factors that form part of a trans-regulatory pathway that alters the expression of the *apn1* Bt binding receptor in Cry1Ac resistant *T. ni* (Tiewsiri and Wang, 2011). In the current study we also show that down-regulation of *apn1* and *apn3* transcripts in midgut are linked to increased survival of larvae from a laboratory colony of *O. nubilalis* when exposed to Cry1Ab toxin on artificial diet. Furthermore, the genetic control of Cry1Ab resistance by two QTLs are independent of aminopeptidase N loci identifies a complex and polygenic mechanism of trans-regulatory control of Bt resistance in Lepidoptera.

2. Materials and methods

2.1. Dose-response assays and dominance of Cry1Ab resistance

A laboratory colony of *O. nubilalis* with a ≥2500-fold increase in Cry1Ab-toxin tolerance compared to susceptible controls (colony Cry1AbR) was previously selected by Coates et al. (2007), but toxin dose—response assay data were not reported. Cry1Ab toxin overlay bioassay treatments of 0.0, 1.0, 2.5, 5.0, 7.5, 10.0, 25.0, 50.0, 75.0, and 100.0 ng Cry1Ab toxin × cm⁻² were prepared as described by Marcon et al. (1999). Three replicates of 16 *O. nubilalis* neonates from a Cry1Ab susceptible colony (Cry1AbS) were exposed to Cry1Ab toxin on overlay diet for 7 d. Similarly, three replicates of 16 neonates from Cry1AbS reared on 0.0, 10.0, 100.0, 500.0, 1000.0, 5000.0, 7500.0, 10000.0 and 12500.0 ng Cry1Ab toxin × cm⁻² for 7 d. Survival was scored as larvae that molted to ≥2nd instar, and lethal concentration required to cause 50% (LC50) and 99% (LC99) mortality were calculated according to Marcon et al. (1999).

Dominance of the Cry1Ab resistance trait was estimated from cross started between ~50 Cry1AbR and ~50 Cry1AbS adults. Subsequent reciprocal backcrosses were preformed en masse between ~25 % F1s (S) and ~25 % from the Cry1AbR (rr) or Cry1AbS (SS) lines. Neonates from Cry1AbR and Cry1AbS colonies, F1s, and reciprocal backcrosses were exposed to a diagnostic 200.0 ng Cry1Ab toxin × cm⁻² dose of 7 d as described above. Dominance of relative fitness (DFR) conferred by the resistance allele(s) of the Cry1AbR strain when subjected to Cry1Ab toxin overlays of 200 ng cm⁻² was calculated an interpreted as a relative measure of dominance level of fitness (h) according to Bourguet et al. (2000).

2.2. Correlation of *apn* transcript level with Cry1Ab resistance

Midguts were dissected from twelve 5th instars from the Cry1AbR, Cry1AbS, F1, and reciprocal backcross progeny (generated by mating en masses in the prior section), flash frozen in liquid nitrogen, and total RNA extracted as described by Coates et al. (2008b). RNA was quantified on a Nanodrop ND-2000 (Thermo Scientific, Wilmington, DE) at 240 nm and ~750 ng was used template for 1st strand cDNA synthesis using the Abgene Reverse-IT kit according to manufacturer instructions. Real time RT-PCR assays were run for *O. nubilalis* *apn1* (onap1), onap2, onap3, and onap4 in triplicate 25 μl real-time RT-PCR reactions that included 12.5 μl iQ SYBR Green reaction mix (BioRad, Hercules, CA), 5.0 pmol each of primer (Table S1), and 2.0 μl 1st strand cDNA (diluted 1:10 with nuclease free water). Reactions were amplified on an iQ thermocycler (BioRad) at 95 °C for 3 min, then 40 cycles of 95 °C 30 s, 60 °C for 30 s, and 72 °C for 10 s followed by melt curve analysis (55 °C for 10 s, +0.5 °C cycle for 80 cycles) with fluorescence measured at 490 nm. Cycle threshold (Ct) was estimated from background subtracted data and transcript levels were normalizing to β-actin using the 2⁻ΔΔCt method (Livak and Schmittgen, 2001). The relationships between transcript levels and proportion of genetic background from the Cry1AbR colony from Cry1AbR, Cry1AbS, F1, and reciprocal backcross groups was assessed with the Pearson product moment correlation coefficient (PMCC) using SAS 9.2 (SAS Institute). Data were comprised of mean transcript levels from individual samples estimated from RT-PCR reactions run in triplicate of each aminopeptidase. Neonicotinoid primers were designed to amplify onap2 (GenBank accessions EU686652.1–EU686655.1) and onap3 genes.
from *O. nubilalis* (GenBank accession JF308287) using Primer3 (Table S1). The onapn1, onapn2, onapn3, onapn4 and onapn5 gene fragments were PCR amplified according to Coates et al. (2008b, 2009) to screen the *O. nubilalis* BAC library, OnB1, using methods described by Coates et al. (2009). DNA from OnB1 library clones were isolated and quantified as described by Coates et al. (2009), and ~0.5 µg digested with 0.5 U of EcoRI, PstI, or EcoRI + PstI for 5 h. Entire digested products were separated on a 0.8% TAE gel at 50 V for 8 h using Lambda EcoRI + HindIII digest as a molecular weight standard, and fragment sizes estimated using Chemidoc XR software (BioRad). Fragment size estimates from gel images were entered into the program FPC and restriction maps assembled in default parameters (Soderlund et al., 1997).

OnB1 library clones 04G20, 50L07, and 55M15 were cultured, and DNA isolated and sequenced on a Roche 454 at the University of Illinois, William H. Keck Center for Comparative and Functional Genomics as described by Coates et al. (2012). Raw data was assembled using GS De Novo Assembler v2.3 default parameters (Seed step: 12, Seed length: 16, Min overlap length: 40, Min overlap identity: 90%, Alignment identity score: 2, and Alignment difference score: 23), and all of the non-redundant contigs were exported to a file in FASTA format by software provided by the manufacturer. Contig data was imported into a local nucleotide database and queried with *Bombyx mori* aminopeptidase N protein sequences from gene models BGIIBMGA001641, BGIIBMGA001642, BGIIBMGA008017, BGIIBMGA008018, and BGIIBMGA008059 thru BGIIBMGA008063 using the tblastn algorithm, and results filtered for hits with E-values <1 × 10^-25. Gene coding regions were annotated within contig sequence using the program Sequin and submitted to the GenBank nr database.

2.3.2. Mapping quantitative trait loci involved in *Cry1Ab* resistance

A biphasic linkage mapping approach was used as described by Heckel et al. (1999) to establish pedigrees initiated from a single parental mate pair of a *Cry1Ab* resistant female (rr); *P. ricini* × susceptible male (SS); *P. sordidella*, and subsequent backcross families that were derived from an *F_1* male × *Bt* resistant female (*F_1*SS × BCPrr; pedigree BC3C) or a reciprocal *F_1* female × resistant male (*F_1*SS × BCPref; pedigree BC4E). A total of 28 neonates from each backcross were reared on semi-meridic diet (untreated control). All remaining reciprocal backcross progeny were phenotyped following a 7-day sub-lethal toxin exposure as described by Coates et al. (2007). DNA was extracted from initial parents *P. ricini* and *P. sordidella*, BC3C and BC4E backcross parents, and untreated control and *Cry1Ab*-phenotyped individual using the Qiagen Blood and Tissue Extraction Kit (Qiagen, Valencia, CA) according to manufacturer instructions and quantified on a Nanodrop ND-2000 (Thermo Scientific, Wilmington, DE).

DNA was prepared for amplified fragment length polymorphism (AFLP) assays and used with 24 selective primer pairs in AFLP-PCR as described by Coates et al. (2011a). DNA not used for AFLP template generation was diluted to 10 ng µl^-1^ using deionized nuclease free water, and genotyped using SNP markers previously developed for the candidate Bt-resistance genes *brainiac* (*brn*), cadherin (*cad*), and aminopeptidase N (*onapn2 and onapn3*) (Coates et al., 2005, 2007, 2008a,b). Additionally, 763 *O. nubilalis* SNP markers were assayed Sequenom MassARRAY® at the Iowa State University Center for Plant Genomics (ISU-CPG; Ames, IA, USA) as previously described by Coates et al. (2011b). Genotypes from AFLP and SNP markers segregating among backcross progeny from heterozygous *F_1*SS (backcross BC3C) or *F_1*SS (backcross BC4E) and a corresponding homozygous backcross parents BCPrr (BC3C) or BCPref (BC4E) were pooled by backcross, and predicted 1∶1 Mendelian genotypic ratios inheritance were tested using the χ² statistic (P cutoff > 0.05). Mendelian inherited SNP markers were input into MAPMAKER 3.0 (Lincoln et al., 1992) and linkage associations among markers were determined using the Kosambi mapping function with cutoffs of LOD ≥ 2.0 and r ≤ 0.35. Graphics created using MapDraw v. 2.1 (Liu and Meng, 2003).

3. Results

3.1. Dose-response assays and dominance of *Cry1Ab* resistance

Results of *Cry1Ab* toxin overlay assay indicated that the estimated LC₅₀ for larvae *Cry1Ab* R (9.2 ± 1.6 ng *Cry1Ab* toxin × cm⁻²) was >1359-fold lower compared to *Cry1Ab* S (Fig. S1). Confidence intervals for the LC₅₀ estimate from the *Cry1Ab* R strain could not be calculated due to insufficient larvae mortality even after high *Cry1Ab* toxin exposures. Regardless, the lower level of the confidence interval at 12,500.0 ng *Cry1Ab* toxin × cm⁻² was used to extrapolate an LC₅₀ value of ≤13,853 ng *Cry1Ab* toxin × cm⁻². The LC₅₀ value for the *Cry1Ab* S strain was significantly higher than that estimated for *Cry1Ab* R (Student’s t-test statistic = 4.02 × 10⁻⁴⁰⁰, P-value = 0.0005). The LC₉₉ estimate for the *Cry1Ab* S strain was 97.5 ± 2.1 ng *Cry1Ab* toxin × cm⁻², and was used to set a minimum dose of 200 ng *Cry1Ab* toxin × cm⁻² that as the diagnostic dose to separate resistant and susceptible phenotypes.

Exposure of neonates from the *Cry1Ab* S strain and backcross progeny from *F_1* × *Cry1Ab* S crosses to a diagnostic toxin concentration of 200 ng *Cry1Ab* toxin × cm⁻² resulted in zero and ≤6.25% survivorship after a 14 d exposure. In contrast, larvae from *F_1*, *F_1* × *Cry1Ab* S backcross and the *Cry1Ab* S strain respectively showed 37.82 ± 11.39%, 77.31 ± 6.81%, and 93.75% survival (Fig. 1). The slope of the survivorship curve showed a positive correlation
with increasing proportions of genetic background from the Cry1Ab\(^R\) strain, and is consistent with a partially additive genetic component of the trait. Thus, if the phenotypic value of the homozygote (rt) = 2a = 1.0000, then the corresponding phenotypic value of the heterozygote (rS) = 0.3782 + 0.9375 = 0.4034 compared to 0.5 for pure additive traits. Incomplete dominance, \(D_{W1} = h = 0.40\), was demonstrated for the Cry1Ab resistance trait using survivorship percentages among the Cry1Ab\(^R\), Cry1Ab\(^S\) and F1 heterozygote groups.

### 3.2.2. Association between reduced apn transcript levels and Cry1Ab resistance

The mean transcript level estimated among Cry1Ab\(^S\), F1, and reciprocal backcross progeny were reduced for all aminopeptidase N genes, but the decrease was most pronounced for onapn1 and onapn3 (Fig. 1). The PMCC of these data showed a strong correlation between of mean apn1, transcript level mean survivorship among larvae from Cry1Ab\(^R\) and Cry1Ab\(^S\) colonies (\(R^2 = 0.99; P < 0.001\)), as well as among groups of larvae with increasing levels of genetic background from the Cry1Ab\(^R\) colony (Fig. 1; \(R^2 = 0.76; P < 0.001\)). Similarly, onapn 3 transcript levels also showed a significant correlation with increasing proportion of Cry1Ab\(^R\) background (\(R^2 = 0.91; P < 0.001\)). No other transcript levels showed any significant correlations (remaining results not shown). Since increasing genetic background from the Cry1Ab\(^R\) colony was positively correlated with increased survival on Cry1Ab toxin bioassays, corresponding correlation between decreased onapn1 and onapn3 transcript levels and increasing genetic background from the Cry1Ab\(^R\) colony was extrapolated to also include association between transcript levels and Cry1Ab resistance.

### 3.3. Mapping of Cry1Ab resistance in O. nubilalis

#### 3.3.1. Physical mapping of the aminopeptidase N gene family

Twelve BAC clones from the OnB1 library were identified using onapn1, onapn2, onapn3, and onapn4 markers (37 PCR positives, mean of 2.65 ± 0.84 markers per insert; Fig. 2A). BAC fingerprints from 9 of 12 clones (75%) were used to generate an approximate 182 kb physical map representative of the O. nubilalis genome interval and determine a minimum tiling path for subsequent DNA sequencing (Fig. 2B). A total of 20.4 and 17.1 Mb of raw Roche GS-FLX data was obtained from libraries created for OnB1 clone 04G20 and 55M15, and was assembled into 3 contigs using the Newbler Assembler; 2 from clone 04G20 (GenBank accession JF339038 and JF339039) and a single contig from 55M15 (JF339040). Query of BAC contigs with onapn1, onapn2, onapn3, onapn3a, onapn4 and onapn8 cDNAs using the blastn algorithm, and B. mori aminopeptidase N proteins using the blastx algorithm

### Table 1

| Colony       | Mean onapn1 C\(_T\) | Mean \(\beta\)-actin C\(_T\) | \(\Delta C_T\) (avg. onapn1 C\(_T\) – avg. \(\beta\)-actin C\(_T\)) | \(\Delta C_T\) (avg. \(\Delta C_T\) Cry1Ab\(^R\)) | Normalized onapn1 relative to Cry1Ab\(^R\) |
|--------------|---------------------|-----------------------------|----------------------------------------------------------|-------------------------------------------------|------------------------------------------|
| A) onapn1    |                     |                             |                                                          |                                                 |                                          |
| Cry1Ab\(^S\) | 28.5                | 27.0                        |                                                          |                                                 |                                          |
| 28.3         | 26.6                |                             |                                                          |                                                 |                                          |
| 28.7         | 26.7                |                             |                                                          |                                                 |                                          |
| 28.6         | 27.0                |                             |                                                          |                                                 |                                          |
| 28.6         | 26.9                |                             |                                                          |                                                 |                                          |
| 28.3         | 26.8                |                             |                                                          |                                                 |                                          |
| Avg.         | 28.5 ± 0.15         | 26.83 ± 0.15                | 1.67 ± 0.30                                              | 0.00 ± 0.30                                     | 1.02 ± 0.21                             |
| B) onapn3    |                     |                             |                                                          |                                                 |                                          |
| Cry1Ab\(^S\) | 24.4                | 26.02 ± 0.15                | 1.78 ± 0.30                                              | 146.21 ± 17.39                                  |                                          |
| 24.4         | 24.5                | 29.9                        |                                                          |                                                 |                                          |
| 24.6         | 30.0                |                             |                                                          |                                                 |                                          |
| 24.3         | 30.0                |                             |                                                          |                                                 |                                          |
| 24.5         | 29.8                |                             |                                                          |                                                 |                                          |
| Avg.         | 24.45 ± 0.10        | 29.97 ± 0.09                | -5.52 ± 0.17                                             | -7.18 ± 0.17                                    | 146.21 ± 17.39                          |
| Cry1Ab\(^R\) | 26.1                | 26.8                        |                                                          |                                                 |                                          |
| 26.3         | 27.0                |                             |                                                          |                                                 |                                          |
| 26.2         | 26.6                |                             |                                                          |                                                 |                                          |
| 26.3         | 26.7                |                             |                                                          |                                                 |                                          |
| 26.1         | 27.0                |                             |                                                          |                                                 |                                          |
| 26.0         | 26.9                |                             |                                                          |                                                 |                                          |
| Avg.         | 26.17 ± 0.11        | 26.83 ± 0.15                | 1.67 ± 0.30                                              | 0.00 ± 0.30                                     | 1.02 ± 0.21                             |
| Cry1Ab\(^S\) | 26.9                | 30.0                        |                                                          |                                                 |                                          |
| 26.3         | 30.1                |                             |                                                          |                                                 |                                          |
| 26.0         | 29.9                |                             |                                                          |                                                 |                                          |
| 26.3         | 30.0                |                             |                                                          |                                                 |                                          |
| 26.8         | 30.0                |                             |                                                          |                                                 |                                          |
| 26.8         | 29.8                |                             |                                                          |                                                 |                                          |
| Avg.         | 26.52 ± 0.33        | 29.97 ± 0.09                | -3.45 ± 0.39                                             | -2.78 ± 0.39                                    | 7.10 ± 1.90                             |

Cry1Ab\(^S\) and Cry1Ab\(^R\) are respectively the B. thuringiensis Cry1Ab toxin resistant and susceptible lines.
A plot of the mean deviation in genotypic proportions for SNP marker, Contig05855.192, showed no linkage to any other marker. Specified independent of LG24 or LG27, and showed no significant deviation from Mendelian proportions among Cry1Ab survivors. Specifically, onapn1, onapn2, onapn3, onapn3a, onapn4, onapn5, onapn6, onapn7 and onapn8 are shown.

resulted in the prediction of intron-exon structure for onapn3b, onapn3c, onapn5, onapn6, and onapn7 genes (Fig. 2C).

3.3.2. Quantitative trait loci involved in Cry1Ab resistance

Inheritance of larval O. nubilalis Cry1Ab resistance was evaluated within a biphasic pedigree, which exploits the lack of meiotic crossover during lepidopteran oogenesis to identify resistant female-derived markers that co-segregate with the trait. Pedigrees BC3C chromosomes were inherited as a single haplotype from the initial resistant female parent (F$_r$) through all of backcross progeny. A total of 156 SNP markers were heterozygous in the F$_1$ parent and homozygous BCP$_r$ resistant line parent, and thus segregating among BC3C backcross progeny. Chi-square ($\chi^2$) tests indicated that genotypes from 140 markers (File S1) did not significantly deviated from a predicted 1:1 Mendelian proportion among 22 backcross progeny reared on control diet ($P \geq 0.0887$; Table S2). Genetic linkage analysis of Mendelian-inherited SNP markers from control group progeny resulted in a map consisting of 126 markers on 31 linkage groups (LGs; 4.06 ± 2.24 SNP markers per LG; Table S3).

Analogous genotypes from full-sib BC3C progeny that had molted to 2nd instar on Cry1Ab diet (Cry1Ab resistant group; File S1) had 11 makers of these 140 SNP markers which were non-Mendelian. Seven of the 11 non-Mendelian SNP markers (63.6%) were on LG24 ($P \leq 0.01058$) and 3 (27.3%) were on LG27 ($P \leq 0.00493$; $\chi^2$-statistic results in Table S2). One non-Mendelian marker, Contig05855.192, showed no linkage to any other marker. A plot of the mean deviation in genotypic proportions for SNP markers located on the 31 O. nubilalis LGs showed that markers on LG24 significantly deviated from Mendelian expectation ($P_{\text{mean}} = 0.0059 \pm 0.0023$) as did markers on LG27 ($P_{\text{mean}} = 0.0403 \pm 0.0160$; Fig. 3). The significance of deviations from Mendelian expectations did not surpass a Bonferroni adjusted $\alpha = 0.05/31 = 0.0016$ for either LG24 or LG27. Results also showed that SNP in candidate Bt toxin binding protein genes segregated independent of LG24 or LG27, and showed no significant deviation from Mendelian proportions among Cry1Ab survivors. Specifically, onapn1 and onapn4 mapped to LG02, brainiac/bre5 to LG03, ABC transporter to LG12, and cadherin to LG14, and alleles from the initial resistant female were equally likely among backcross progeny from Cry1Ab or control diet (Table S3).

Pedigree BC4E consisted of an F$_{r}$ parent backcrossed to a resistant BCP$_r$ parent, and the resulting BC4E progeny were recombinants of the Cry1Ab resistant haplotypes inherited from the initial Cry1Ab resistant female parent (P$_{rr}$). SNP genotyping of BC4E backcross parents and progeny was conducted only for multiplex reactions that contained markers linked to the QTL for Cry1Ab (LG24), and a set of 24 AFLP primer pairs that were used to increase marker density on LG24. Analysis of SNP and AFLP genotypes from BC4E untreated control progeny (File S2) showed that SNP markers Contig00519.709, Contig03610.309, Contig05998.290, and Contig06606.695 along with 2 AFLP markers E-ACC700_M-TG0160 and E-AGC800_M-TG0177 were Mendelian ($P$-values $\geq 0.1573$; Table S4) and co-segregating on LG24 (22.46 cM genome interval) between markers; Fig. 4). Data from the same markers from BC4E larvae that had molted to 2nd instar on Cry1Ab toxin diet (File S2) showed that Contig03610.309, Contig05998.290, E-ACC700_M-TG0160, and E-AGC800_M-TG0177, deviated significantly from expected 1:1 Mendelian ratios ($P$-values $\leq 0.0310$; Table S4), with the greatest deviation estimated for AFLP marker E-ACC700_M-TG0160 ($P = 0.0039$) that surpassed the Bonferroni adjusted $\alpha = 0.0016$ (Fig. 4). In contrast, no significant deviation was detected for markers on LG27 in backcross BC4E, Contig00519.709 ($P = 0.0599$) or Contig06606.695 ($P = 0.1823$), despite an indication of significance in backcross BC3C.

4. Discussion

Transgenic crops that express Bt crystalline insecticidal protein toxins have shown remarkable success at suppressing pest insect damage in instances where “high-dose” events are capable of causing mortality among 100% of homozygous susceptible and heterozygous individuals (Huang et al., 2011). In contrast, resistance rapidly developed to “low-dose” events within populations of the coleopteran insect, Diabrotica virgifera virgifera (Cassmann et al., 2011). Success of IRM strategies for Bt crops has also benefitted from resistant insect phenotypes that have an
effective dominance ($h$) of zero, wherein heterozygote genotypes are functionally susceptible. In recent years, lepidopteran insect populations have evolved resistance traits that enable larval survival and development on transgenic Bt crops in field conditions (Kranthi, 2005; van Rensburg, 2007; Li et al., 2007; Matten et al., 2008; Tabashnik et al., 2008), where dominant alleles have been characterized among Cry1Ac resistant Helicoverpa armigera and Helicoverpa zea (Tabashnik et al., 2008; Zhang et al., 2012). A similar incomplete recessive nature of Bt resistance was also described among Plutella xylostella that survived exposure to foliar Bt sprays (Tabashnik et al., 1997), as well as among laboratory selected Cry1C resistant Spodoptera littoralis (Chaufaux et al., 1997) and Cry1Fa resistant O. nubilalis (Pereira et al., 2008). Although estimates of relative fitness depends upon conditions in which the trait is measured, the Cry1Ab toxin resistance trait in the O. nubilalis Cry1Ab<sup>R</sup> colony ($D_{WT} = h = 0.40$) suggests that resistant alleles are nearly co-dominant. The observation of consistent field suppression of O. nubilalis populations (Hutchison et al., 2010) suggests that current commercialized “high-dose” Cry1Ab events may cause this trait to be irrelevant in terms of resistance evolution (Bourguet et al., 2000), but provide an additional instances where complete recessive behavior of resistance alleles cannot be assumed under the HDR strategy.

The genetic basis of Cry1A and Cry1F resistance traits have been shown to be controlled by single genes or genetic loci (Gahan et al., 2001, 2010; Morin et al., 2003; Baxter et al., 2008; Coates et al., 2011a,b; Zhang et al., 2012). In contrast, Cry1Ac resistance in the laboratory-selected H. virescens YHD2 strain was shown to be polygenic through the involvement of cad and abcc2 genes (Gahan et al., 2001, 2010). Chronic exposure to low levels of Bt toxin in laboratory selection schemes have been suggested to favor the accumulation of insecticide resistance traits based upon many genes of small effect (polygenic; Groeters and Tabashnik, 2000). Similarly, the O. nubilalis Cry1Ab<sup>R</sup> strain was exposed to sub-lethal levels of Cry1Ab toxin during selection (Coates et al., 2007), such that the additive genetic component predicted to involve >1 gene could be an artifact of laboratory selection. Regardless, the O. nubilalis Cry1Ab resistance described in this research may provide a model for the genetic effects of sub-lethal exposure on target pest insects, any might have relevant analogies to field selection from “low-dose” transgenic corn events that are currently used (e.g. Bt corn hybrids commercialized for the control of D. v. virgifera).

The molecular basis of Bt resistance traits in Lepidoptera have been linked to mutations that cause changes in protein structure or transcript abundance (and corresponding protein abundance) compared to susceptible individuals (see Introduction). A constitutive decrease in apr1 transcript level was correlated with the Cry1Ab toxin resistance trait in the O. nubilalis Cry1Ab<sup>R</sup> strain in our experimental design, and was also previously shown to be the basis of Cry1Ca resistance in S. exigua, and Cry1Ac resistance in H. armigera (Zhang et al., 2009) and T. ni (Tiewsiri and Wang, 2011). Similar to onapn1, our results showed that onapn3 transcripts decreased in response to increasing Cry1Ab<sup>R</sup> genetic background and were also likewise significantly correlated with inheritance of Cry1Ab resistance trait. The fold reduction and degree of onapn3 linkage to Cry1Ab resistance was lower compared to onapn1, which could suggest that onapn1 and onapn3 might share common regulatory control factors. Furthermore, the potential intertwined regulatory control as well as tight genetic linkage between onapn1 and onapn3 (see below) may interject difficulties in the dissection of independent contributions of these genes to the Cry1Ab<sup>R</sup>
resistance trait. These reports suggest that mutations which affect the transcription of membrane-bound aminopeptidase N genes is likely to decrease subsequent translation such that the protein receptor is effectively eliminated from the midgut epithelium. The reoccurrence of apn1 transcript suppression as a potential mechanism for Cry1 toxin resistance suggests that APN1 (and potentially APN3) is a critical binding receptor in the Cry1 toxin mode of action in Lepidoptera. Indeed, both apn1 and apn3 orthologs are known to bind Cry1A toxin in other species of Lepidoptera (reviewed by Piggot and Elfar, 2007). Post-translational glycosylation of T. ni apn3 was shown to be a requirement for Cry1A binding (Gill et al., 1995; Garner et al., 1999), and suggested that in vivo insect cell expression systems are necessary for proper binding analyses. Subsequent expression of H. armigera apn3 in T. ni cell lines demonstrated the capacity to bind Cry1Ac, but not Cry1Ab or Cry1Aa (Rajagopal et al., 2003). Similar results were obtained from purified endogenous apn3 from L. dispar (Valaitis et al., 1997). In contrast, the O. nubilalis apn3a isoform was shown only to bind Cry1Fa when expressed in SF21 cells (Crava et al., 2013). apn1 has repeatedly been shown to be involved in Cry1A resistance mechanisms of lepidopteran species (see Introduction). Since the control of gene expression can be enacted through a network of interconnected genetic factors or multiple pathways that are often co-regulated within a biological system (Jowett and Phillips, 2009), genes within the apn gene family may retain shared ancestral regulatory mechanisms. It is conceivable that correlation of decreased onapn3 transcription with Cry1Ab resistance may be a consequence of placement within the same gene regulatory network as onapn1, and that correlation of onapn3 with Cry1Ab resistance results from mutations in trans-acting regulatory factors that modulate the major Cry1Ab binding receptor (onapn1). Understanding the genetic control of apn transcripts may be important for deciphering of mechanism(s) involved in Cry1 resistance in lepidopteran species, and will be a focus of future studies.

Using evidence from the segregation of genetic markers, Coates et al. (2008a) previously showed that the onapn1 locus was independent of the Cry1Ab resistance trait in the same O. nubilalis Cry1Ab
 strain used in this study. This was not surprising since loci for candidate Bt binding receptors have been shown not to be linked to associated resistance traits (Baxter et al., 2008; Coates et al., 2011a,b), but such studies have the major drawback of limiting the genomic loci at which associations can be made with the trait (Tabor et al., 2002; Wayne and McIntyre, 2002). In our current analyses the genetic location of onapn1 was predicted on LG2, which was unlinked and segregating independently of QTL identified on LG24 and LG27. These QTL results confirmed previous observations by Coates et al. (2008a), as well as our phenotypic evidence which suggested that Cry1Ab resistance in the Cry1Ab
 colony has an additive (polygenic) genetic component. QTL results also suggested that genetic factors on LG24 and LG27 may be controlling transcription of onapn1 on LG2. Specifically, mutations that decrease the transcription at a genetic locus may be caused by changes in cis- or trans-regulatory mechanisms. Since genes are physically linked to proximal cis-regulatory elements (promoters or enhancers) chromosomal segregation or recombination are not likely to cause significant linkage disequilibrium between the causal gene and QTL. In contrast, trans-regulatory control of a gene can be mediated by soluble protein factors that bind cis-promoter or enhancer elements, such that gene products that act as trans-regulatory factors (transcription factors) move within the nucleus to affect transcription at unlinked loci. Although not a novel concept in genetics, the control of transcription for a Bt toxin receptor and associated resistance traits by putative mutations in trans-acting regulation has only been described once previously (Tiewsiri and Wang, 2011), but reinforces that complexities of gene interactions (epistasis) can contribute to phenotypic variance.

Since the reduced expression of apn1 has a role in Cry1 resistance traits from multiple lepidopteran species, deciphering the genetic control of this gene in Lepidoptera may be important in order to understand the evolution of these resistance mechanisms. Seven aminopeptidase N genes are duplicated in tandem in the B. mori genome, which agreed with prior inference that a duplication of apn genes was ancestral to the lepidopteran lineage (Chang et al., 1999; Angelucci et al., 2008). Seven apn—like paralogs were defined from O. nubilalis cDNA (Crava et al., 2010) and were subsequently identified in physically overlapping genomic inserts from two O. nubilalis BAC clones in this study. When compared to B. mori genome assembly, a lineage-specific duplication of onapn3 was suggested by prediction of the onapn3 gene (Crava et al., 2010) and confirmed by our BAC insert sequences that contained onapn3a and onapn3b, but assembly predicted presence of a third paralog, onapn3c. This suggest that sequencing of genome intervals might be more successful for the identification of genes compared to cDNA-based methods due to lack of transcriptional dependence.

5. Conclusions

Mutations that create variance in gene interactions (epistasis) in a population lead to novel phenotypes that are manifested within the context of a given environmental condition, therefore differences in transcription-level regulation and interactions among different alleles in unique genome architectures contribute to phenotypic diversity (West et al., 2007). Regulatory mutations have previously been shown to be the likely cause of a Cry1Ac resistance trait (Tiewsiri and Wang, 2011), but in the currently study we uniquely show that two independent genetic loci affect the co-regulation of apn1 and apn3 transcription occurs in trans. Furthermore, control of expression in the aminopeptidase N gene network shows interconnectedness through the co-regulation of onapn1 and onapn3. Unraveling the mechanism used to regulate the expression of this gene family may lead to a better understanding of the genetic basis of Cry1A resistance in Lepidoptera.

Acknowledgments

This research was a joint contribution from the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) (CRIS Project 3625-22000-017-00), the Iowa Agriculture and Home Economics Experiment Station, Ames, IA (Project 3543), and the University of Nebraska. Funding also was provided by a USDA, National Institute of Food and Agriculture (NIFA) (Award Number 2009-05246). The authors wish to thank USDA Technicians Bob Gunnarson, Cindy Backus and Jean Dyer for contributions to genotyping and insect rearing procedures. This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or a recommendation by USDA, Iowa State University or the University of Nebraska for its use.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ibmb.2013.09.003.

References

Alstad, D.N., Andow, D.A., 1995. Managing the evolution of insect resistance to transgenic plants. Science 268, 1894–1896.
Huang, F., Androw, D.A., Buschman, L.L., 2011. Success of the high-dose/refuge resistance management strategy after 15 years of Bt crop use in North America. Ed. Appl. Dev. Stud. 10.1016/j.adm.2011.07.001.

Hutchinson, W.D., Burkhart, E.C., Mitchell, P.D., Moon, R.D., Leslie, T.W., Fleischer, S.J., Abrahamson, M., Hamilton, K.L, Steffey, K.L., Gray, M.E., Mellin-Hill, I.R., Kaster, V., Hunt, T.E., Wright, R.J., Pescovinio, K.T., Rabaey, T.L., Flood, B.R., Rashid, R.E.S., 2010. Assessment of European Bt maize with Bt maize reaps savings to non-Bt maize growers. Science 330, 222–225.

Jamaat, A., Myers, J., 2003. Rapid evolution and the cost of resistance to Bacillus thuringiensis in greenhouse populations of cabbage loopers, Trichoplusia ni (Lepidoptera: Noctuidae). J. Econ. Entomol. 96, 356–370.

Jurat-Fuentes, J.L., Gauld, F.L., Adang, M.J., 2002. Altered glycosylation of 63- and 68-kilodalton microvillar proteins in Heliotis virescens correlated with reduced Cry 1 toxin binding, decreased pore formation, and increased resistance to Bacillus thuringiensis Cry1Ab toxin. Microbiol. 68, 5711–5717.

Jovelin, R., Phillips, P.C., 2009. Evolutionary rates and centrality in the yeast gene regulatory network. Genome Biol. 10, R35.

Kranthi, K.R., 2005. Bollworm resistance to Bt cotton in India. Nat. Biotechnol. 23, 1476–1477.

Labbé, P., Berticat, C., Berthoumieu, A., Unal, S., Bernard, C., Weill, M., Lenormand, T., 2007. Forty years of erratic insecticide resistance evolution in the mosquito Culex pipiens. PLoS Genet. 3, 2190–2199.

Lincoln, S., Daly, M., Lander, E., 1992. Constructing Genetic Maps with MAPMAKER/EXP 3.0. third ed. Whitehead Institute (Technical Report).

Li, G., Wu, K., Gould, F., Wang, J., Miao, J., Gao, X., Guo, Y., 2007. Increasing tolerance to Cry1Ac cotton from cotton bollworm Helicoverpa armigera, was confirmed in Bt cotton farming areas of China. J. Econ. Entomol. 27, 365–370.

Liu, R.H., Meng, J.L., 2003. MapDraw: a Microsoft Excel macro for drawing genetic linkage maps based on given genetic linkage data. Hereditas (Beijing) 25, 317–321.

Livak, K.J., Schmittgen, T.D., 2001. Analysis of relative gene expression data using real-time quantitative PCR and the 2(-Delta Delta C(T)) method. Methods 25, 402–408.

Marcon, P.C.R.G., Siegfried, B.D., Spencer, T.A., Hutchison, W.D., 1999. Development of diagnostic concentrations for monitoring Bacillus thuringiensis resistance in European corn borer (Lepidoptera: Crambidae). J. Econ. Entomol. 93, 925–930.

Matten, S.R., Head, G.P., Queinada, H.D., 2008. How governmental regulation can help smooth the integration of Bt crops into IPM programs. In: James, J., Sheldon, A.M., Kennedy, G.C. (Eds.), Integration of Insect-resistant Genetically Modified Crops within IPM Programs. Springer, New York, pp. 27–39.

Morin, S., Biggs, R.W., Sisterson, M.S., Shriver, L., Ellersiek, C., Higgsdon, D., Gahan, L., Carriere, Y., Dennehy, T., Brown, J.K., Tabashnik, B.E., 2003. Three cadherin alleles associated with resistance to Bacillus thuringiensis in pink bollworm. Proc. Natl. Acad. Sci. U. S. A. 100, 5004–5009.

Pereira, E.J.G., Storer, N.P., Siegfried, B.D., 2008. Inheritance of Cry1F resistance in laboratory-selected European corn borer and its survival on transgenic corn expressing the Cry1F toxin. Bull. Entomol. Res. 98, 621–629.

Pigott, C.R., Ellar, D.J., 2007. Role of receptors in Bacillus thuringiensis crystal toxin action. Microbiol. 68, 275–281.

Rajagopal, R., Agrawal, N., Selvapandian, A., Sivakumar, A., Ahmad, S., Bhatnagar, R.K., 2003. Recombinantly expressed isozymic aminopeptidases from Helicoverpa armigera midgut display differential interaction with closely related Cry Cry proteins. Insect Biochem. Mol. Biol. 33, 971–981.

Soderlund, C., Longden, I., Mott, R., 1997. FPC: a system for building contigs from restriction fragment data. Comput. Appl. Biosci. 13, 523–535.

Tabashnik, B.E., Chushing, N.L., Finson, N., Johnson, M.W., 1990. Field development of resistance to Bacillus thuringiensis in diamondback moth (Lepidoptera: Plutellidae). J. Econ. Entomol. 83, 1671–1676.

Tabashnik, B.E., Liu, Y.B., Malvar, T., Heckel, D.G., Masson, L., Ballester, V., Granero, F., Mensa, J.L., Ferre, J., 1997. Global variation in the genetic and biochemical basis of diamondback moth resistance to Bacillus thuringiensis. Proc. Natl. Acad. Sci. U. S. A. 94, 12788–12785.

Tabashnik, B.E., Liu, Y.B., Malvar, T., Heckel, D.G., Masson, L., Ballester, V., Granero, F., Mensa, J.L., Ferre, J., 1997. Global variation in the genetic and biochemical basis of diamondback moth resistance to Bacillus thuringiensis. Insect Biochem. Mol. Biol. 27, 529–539.

van Rensburg, J.B.J., 2007. First indications of resistance to Bacillus thuringiensis Cry1F toxin in the South African cotton bollworm, Helicoverpa armigera. J. Insect Sci. 7, 293–301.

Wayne, M.L., McIntyre, L.M., 2002. Combining mapping and arraying: an approach to candidate gene identification. Proc. Natl. Acad. Sci. U.S.A. 99, 14903–14906.

West, M.A.L., Kim, K., Klebenstein, D.J., Leeuwen, H.V., Michelmore, R.W., Doerge, R.W., St. Clair, D.A., 2007. Global eQTL mapping reveals the complex interplay of resistance loci and allele-specific expression with Cry1Ab resistance in B. nil.

US EPA, 2001. Biopesticides Registration Action Document – Bacillus thuringiensis Plant-incorporated Protections. http://www.epa.gov.pesticides/biopesticides/pdfs/blad/brad.html.

van der Bergh, J.R., 2007. First field report of field resistance by the stem borer, Busseola fusca (Fuller) to transgenic maize. S. Afr. J. Plant Soil 24, 147–151.

Valatiss, A.P., Mazza, A., Brousseau, R., Masson, L., 1997. Interaction analyses of Bacillus thuringiensis Cry1 toxin binding proteins in close related Cry proteins. Biochem. J. 312, 277–282.

Wayne, M.L., McIntyre, L.M., 2002. Combining mapping and arraying: an approach to candidate gene identification. Proc. Natl. Acad. Sci. U.S.A. 99, 14903–14906.

West, M.A.L., Kim, K., Klebenstein, D.J., Leeuwen, H.V., Michelmore, R.W., Doerge, R.W., St. Clair, D.A., 2007. Global eQTL mapping reveals the complex interplay of resistance loci and allele-specific expression with Cry1Ab resistance in B. nil.
genetic architecture of transcript-level variation in Arabidopsis. Genetics 175, 1441–1450.
Zhang, S., Cheng, H., Gao, Y., Wang, G., Liang, G., Wu, K., 2009. Mutation of an aminopeptidase N gene is associated with armigera resistance to Bacillus thuringiensis Cry1Ac toxin. Insect Biochem. Mol. Biol. 39, 421–429.
Zhang, H., Tian, W., Jin, L., Yang, J., Liu, C., Yang, Y., Wu, S., Wu, K., Cui, J., Tabashnik, B.E., Wu, Y., 2012. Diverse genetic basis of field-evolved resistance to Bt cotton in cotton bollworm in China. PNAS. http://dx.doi.org/10.1073/pnas.1200156109.