

Review

# Selected Abiotic and Biotic Environmental Stress Factors Affecting Two Economically Important Sugarcane Stalk Boring Pests in the United States

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**Abstract:** Sugarcane, *Saccharum* spp., in the United States is attacked by a number of different arthropod pests. The most serious among those pests are two stalk boring moths in the Family Crambidae: the sugarcane borer, *Diatraea saccharalis* (F.), and the Mexican rice borer, *Eoreuma loftini* (Dyar). The two species are affected by abiotic and biotic environmental stress factors. Water deficit and excessive soil nitrogen alter physical and physiochemical aspects of the sugarcane plant that make the crop increasingly vulnerable to *E. loftini*. Weed growth can be competitive with sugarcane but it also supports enhanced abundances and diversity of natural enemies that can suppress infestations of *D. saccharalis*. In an instance where the stalk borer is considered a stress factor, proximity of vulnerable crops to sugarcane can influence levels of *E. loftini* infestation of sugarcane. The adverse effects of each stress factor, in terms of stalk borer attack, can be reduced by adopting appropriate cultural practices, such as adequate irrigation, judicious use of nitrogen fertilizer, using noncompetitive weed growth, and not planting vulnerable crops near sugarcane fields. Understanding the relationships between stress factors and crop pests can provide valuable insights for plant breeders and tools for incorporation into integrated pest management strategies.

**Keywords:** *Saccharum*; weeds; *Diatraea saccharalis*; *Eoreuma loftini*; Mexican rice borer; sugarcane borer; soil; vegetational diversification; drought; water deficit; corn; maize; resistance; cultivars; cultural practices; irrigation; nitrogen

## 1. The Plant

Sugarcane, *Saccharum* spp., is a perennial crop cultivated on  $\approx$ 20 million ha in tropical and subtropical regions of more than 100 countries [1–3]. Annual yield in terms of stalks is  $\approx$ 1325 million tons harvested for sugar, rum, chemicals, and energy [2,4–7]. In the United States, sugarcane production occurs mainly in Florida, Louisiana, Texas, and Hawaii [8,9]. In 2014, Florida cultivated  $\approx$ 160,300 ha and harvested  $\approx$ 15.2 million tons of sugarcane, Louisiana cultivated  $\approx$ 156,000 ha and produced  $\approx$ 11.5 million tons, Texas grew  $\approx$ 13,400 ha and harvested  $\approx$ 1.2 million tons, and Hawaii had  $\approx$ 6800 ha that produced  $\approx$ 1.3 million tons [8].

The crop is vegetatively propagated by placing cuttings and whole stalks in furrows and covering them with soil. After each harvest the regrowth, or ratoon, grows from the stubble to be harvested the following growing season. In some places it is possible to harvest 20 successive ratoon crops from a single planting [10], but adverse environmental stress factors including weed competition, stalk borer injury, pathogen infection, low winter temperatures, water deficit, poor soil aeration and drainage, and weak cultivar genotypes diminish productivity from one season to the next (termed “stubble decline”), commonly limiting ratoon production to only one or two seasons [11–13].

## 2. The Stalk Borers

Injury to the crop inflicted by herbivorous arthropods represents a biotic stress to the sugarcane plant. Many of the abiotic and biotic factors discussed below (*i.e.*, water deficit, weed competition, soil nitrogen) can exert stress on the sugarcane plant which might affect the herbivore and the amount of damage it causes. Among the herbivorous arthropods that attack sugarcane are stalk boring insects, the sugarcane borer, *Diatraea saccharalis* (F.), and the Mexican rice borer, *Eoreuma loftini* (Dyar) (both Lepidoptera: Crambidae) are the most economically important to sugarcane production in the United States [14].

*Diatraea saccharalis* arose in tropical areas of the Western Hemisphere and it invaded the United States through Louisiana in 1855 [14]. The pest is now established along the United States' Gulf Coast from south Texas to southern Florida, the Caribbean, and Latin America from Mexico to subtropical parts of northern Argentina [14]. Other host plants are maize, *Zea mays* L.; rice, *Oryza sativa* L.; sorghum, *Sorghum bicolor* (L.) Moench; and sudangrass, *Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet and Harlan used as livestock forage, and large-diameter graminaceous weeds including Johnsongrass, *Sorghum halepense* (L.) Pers., *Paspalum* spp., *Panicum* spp., *Holcus* spp., and *Andropogon* sp. [15–18]. In the United States, larvae mostly overwinter in weedy grasses and adults emerge in April and May, followed by 4–5 nonsynchronous generations through autumn [19,20]. Numbers of adults in sugarcane decline during mid-summer [21]. A summer generation requires 25–40 days to complete, and the insect undergoes a form of dormancy during cool winter months [19].

*Diatraea saccharalis* is a “plant vigor insect” that is attracted to plants growing vigorously. The pest oviposits on new leaves and new internodes, the flat oval eggs laid in groups of 2 to >80 [14] mostly on exposed upper and lower surfaces of leaves, particularly near the top to the plant [14]. Hence, the egg stage is vulnerable to a complex of egg predators and parasites [14,22]. For larvae reared on sugarcane and maize, average fecundity is ≈700 eggs, but this declines when larvae are reared on other host plants, including johnsongrass [23]. First instars tend to feed on leaf tissue, sometimes tunneling directly into the midrib; second and third instars bore into the stalk (many move up the stalk before tunneling inside) [19,24]. During warm seasons larval development usually requires 25–30 days (30–35 days in cool weather) and development halts when cold winter temperatures force the insect to overwinter and sometimes to be dormant, often in weeds [25]. Pupation occurs in a chamber that the larva chews within the stalk, a thin “window” of plant tissue remaining as a barrier to predators, parasites, and insecticides [14]. Adults emerge from the pupae in 8–9 days (up to 22 days in cool weather). Moths are yellow or straw-colored with male and female wingspans of 18–28 mm and 27–39 mm wingspans, respectively [14]. The forewing is marked with several brown lengthwise lines and the male hindwing is dusky compared to the white female hindwing. During the 3–8 day adult stage, flight and oviposition mainly occur after dark [14].

Tunneling in mature sugarcane stalks weakens, lodges, and kills upper growth and, in the inner whorl of young plants, tunneling causes “dead heart” (generally does not result in sugarcane plant biomass and sugar yield losses) [19]. Heavy infestations can result in substantial stalk damage, diminishing juice quantity and purity, reducing sucrose yield by 10%–20% [14,25]. The larval tunnels further contribute to production losses by providing portals of entry for infection by red rot, *Colletotrichum falcatum* Went, and other fungi that weaken or destroy stalk tissue and break down sugar [26–29]. Ulloa *et al.* [30] reported that an average of one bored internode per stalk results in 2.5 kg less sugar per ton of harvested sugarcane. While *D. saccharalis* is presently the key pest of sugarcane in Louisiana [31–33], its prevalence might decline once *E. loftini* populations increase and become stabilized there. In south Texas, *E. loftini* supplanted *D. saccharalis* as the key pest of sugarcane soon after its arrival from Mexico in the early 1980s [34–36].

Control of *D. saccharalis* relies mostly on insecticide applications triggered by reaching an economic injury threshold [14,32]. Although biological control using indigenous and exotic parasitoid wasps and parasitic flies has met with some success in Florida [37], it has been less effective elsewhere

in the United States [14]. Entomopathogens such as *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metsch.) Sorok were unable to suppress *D. saccharalis* populations under field conditions [38,39], and although *Bacillus thuringiensis* Berliner was reported to reduce *D. saccharalis* injury to sugarcane stalks by 75% [40], it has not been adopted by growers. Another form of biological control, conservation of natural enemies, is linked with biotic environmental stress factors and can be enhanced by using certain cultural practices. Also, some sugarcane cultivars exhibit resistance traits that offer different degrees of protection [14].

*Eoreuma loftini* is a major sugarcane pest indigenous to western Mexico [26,41]. First detected in the United States in the Lower Rio Grande Valley of south Texas in 1980 [42–44], the insect invaded the rice producing areas of east Texas by 1989 [35,45,46] and Louisiana rice in 2008 [47,48]. By early 2015 *E. loftini* had spread to rice and sugarcane in eight parishes of southern Louisiana [36]. One adult was trapped in Florida in March 2012 and as of late December 2013 more adults have been trapped in Levy and Marion counties and larvae and pupae were detected in fall panicum, *Panicum dichotomiflorum* Michx [49,50]. *Eoreuma loftini* larvae and pupae have been found in at least 17 species of graminous weeds and six crop species (for a list of the known host plants see Showler *et al.* 2011 [51]). Crops most prone to attack are rice, sugarcane, maize, sorghum, and some sorghum and sudangrass hybrids used for livestock forage and feed [14,51–53].

On sugarcane, *E. loftini* mostly oviposits within folds along the edges of dry leaves, although eggs are also deposited in folded green living tissue if it is available [54]. Oviposition occurs relatively low on the plant; 96% of the eggs are located between the soil surface and  $\leq 80$  cm above the soil surface [55]. Egg clusters range from 5 to  $>80$  eggs [55]. Early instars feed on leaf tissue and under fresh leaf sheaths, and some bore into the leaf midrib; later instars tunnel directly into the main stalk [56]. Internodes are most prone to attack during their first 70 days of growth [57], although older internodes are also vulnerable as are new internodes near and at the plant's apex. Tunnels within sugarcane stalks are horizontal and vertical (*D. saccharalis* tunnels are mostly vertical) and so packed with frass that larvae are protected from predators and parasitoids [14,47,53]. Like *D. saccharalis*, late instars chew a chamber inside the stalk and pupation occurs behind a plant tissue "window" [14]. Adults are straw-colored and their unmarked wings are delta-shaped. In the subtropical Lower Rio Grande Valley of Texas, *E. loftini*'s life cycle occurs over 30–45 days, and 4–6 asynchronous generations are produced each year [29,34]. Between  $\approx 260$  and 400 eggs can be produced by a female [34] and all life stages can be found throughout the year [29,55,58]. Substantial numbers of adult *E. loftini* emerge from maize in northern Tamaulipas, Mexico, during February, and populations remain relatively high through midsummer [29]. Peak flight activity in the Texas coastal bend area occurs in March and April, and again in the fall [58].

Protection from natural enemies and many insecticides inside plugged tunnels contributed toward the pest's rapid population expansion in south Texas, where *E. loftini* replaced *D. saccharalis* as the key sugarcane pest [34,59]. Stalk injury from *E. loftini* tunneling diminishes sugar yield and heavy infestations can stunt and lodge stalks so severely that harvest is economically impractical [29,34,47,60]. In south Texas  $\approx 20\%$  of sugarcane internodes were reported as having been damaged particularly by *E. loftini* [61] and in addition to the damage caused by tunnels, the entry and exit holes are portals of infection by red rot. Larval population densities generally do not exceed one larva per sugarcane stalk in the Lower Rio Grande Valley [62] although 50%–80% bored internodes have been reported on some cultivars in Texas [42,43,63]. Estimates of percentage sugar yield loss for every percentage of bored internodes have ranged from 0.5% to 1.3% per ha [61,64]. Economic loss resulting from *E. loftini* injury to south Texas sugarcane has been reported as being US \$575–\$690 per hectare [56,60] and US \$10–\$20 million annually [34,61]. An economic loss projection for Louisiana sugarcane that might be caused by *E. loftini* once it becomes fully established amounted to US \$220 million [35]. Economic projections for Florida are not available.

Early attempts to use insecticides against *E. loftini* have failed to increase sugarcane production in south Texas [60,61] and *E. loftini* sprays were discontinued during the 1990s [34]. More recent research

revealed that some relatively new insecticides can exert acceptable levels of control [65], but their adoption for use against *E. loftini* has not been widespread. In terms of classical biological control, ~27 indigenous and exotic parasitoid wasps and parasitic flies have been released to combat *E. loftini* in the Lower Rio Grande Valley without success [14,53]. Various entomopathogens and entomogenous nematodes have been tried and they also failed under field conditions [14,34,39]. Planting resistant sugarcane cultivars is another way of protecting crop yields against pests, and some cultivars of sugarcane that offer degrees of resistance against *E. loftini* are becoming available and new resistance factors have been identified [14,53,63]. Although some cultural practices (e.g., plowing down sugarcane stubble in fallow fields and selecting optimal planting dates) have been suggested [14,53], they have not been implemented for *E. loftini* management. Other cultural tactics related to environmental factors (discussed in the next two sections) aim to reduce *E. loftini* damage to sugarcane, but it is likely that these examples do not represent all possible ways of manipulating environmental factors to achieve desirable levels of suppression. Research has identified two abiotic environmental stress factors and three biotic environmental stress factors that can be modified with the goal of reducing *E. loftini* infestations.

### 3. Abiotic Environmental Stress Factors

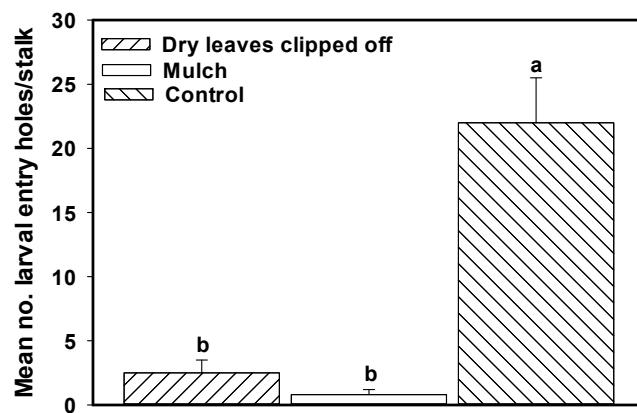
#### 3.1. Water Deficit or Drought Stress

A variety of abiotic factors, some of which induce plant stress, can affect herbivorous pests, including temperature, relative humidity, and photoperiod, but these cannot or are not deliberately manipulated using cultural practices in field-grown commercial sugarcane. While moderate drought stress is harmful to some herbivorous arthropods, it can also increase populations of many herbivorous arthropods that inflict correspondingly more injury to a crop that is already stressed and possibly damaged from the effects of water deficit or from other pests [66]. Drought-enhanced host plant suitability for such insects is typically followed by declining suitability as the stress becomes increasingly severe [67]. The declining suitability occurs because of insufficient water for the pest's requirements and because of host plant tissue desiccation, necrosis, and senescence [66].

Water deficit results in greater abundances of dry leaf tissue on sugarcane stalks than on stalks where sugarcane is grown under well-watered conditions [68,69]. Numbers of *E. loftini* eggs on sugarcane plants have been positively associated with numbers of dry leaves [69,70] which curl or fold at the edges. A laboratory experiment demonstrated that, given a choice between folded green sugarcane leaves, flat dry sugarcane leaves, and folded paper approximately the same color as dry sugarcane leaf tissue, eggs were almost exclusively deposited on the folded green leaves [54]. When folded green leaves were presented alongside dry folded leaves, the dry leaves were used for oviposition [54]. Hence, dryness and folds are both characteristics of sugarcane leaves that are preferred by *E. loftini* for oviposition [54]. A greenhouse no-choice cage assay using potted sugarcane plants from which dry leaf folds were trimmed away with scissors had 93.8% fewer eggs than nontrimmed plants (Figure 1) [54]. Delaying the onset of leaf senescence and reducing the quantity of dried leaves by maintaining adequate soil moisture will minimize the development of sugarcane leaf characteristics that are preferred as oviposition sites. Delaying water deficit-associated leaf drying by judicious irrigation is likely to protect sugarcane from early and possibly midseason infestations that typically injure the lower internodes.

Even after soil dries, normal evapotranspiration rates in most plants often continue for some time [71] by accumulating free amino acids, especially proline, and other organic solutes as osmoregulants [72]. Osmotic stress in plants involves several interconnected molecular pathways that transmit signals and produce stress-response metabolites [73,74], and gene transcripts associated with signaling can be up- or down-regulated within minutes of stress induction [75,76]. As drought conditions continue, plants often have relatively low osmotic potential [77–79], heightened oxidative stress [80,81], and to reduce water loss to the extent possible, accumulations of osmolytes such as

antioxidants, amino acids, carbohydrates, and inorganic ions, altering the attractiveness and nutritional value of the plant to herbivorous arthropods [68–70,82]. Chemical cues (semiochemicals) emitted by plants, frequently involving volatiles, have a major role in host plant selection and utilization by herbivorous arthropods [83–90].



**Figure 1.** Mean ( $\pm$ SE) numbers of *E. loftini* larval entry holes per sugarcane stalk in greenhouse no-choice cage assays where the curls and folds along the edges of dry leaf tissue were excised, dry leaves were placed on the cage floor at a sort of “mulch”, or plants were left intact and without “mulch” as a control; different letters over bars indicate significant differences ( $p < 0.05$ ) [54].

The preference of *E. loftini* to oviposit on drought stressed sugarcane [14,53,68–70] was demonstrated when a sugarcane cultivar resistant to *E. loftini* (L 03-371) under well-irrigated conditions was found to be susceptible under drought conditions (up to 88% bored internodes) [14,53,63,91]. Reay-Jones *et al.* [68] reported that well-irrigated sugarcane was 44% less susceptible to *E. loftini* oviposition and injury to the crop was  $\approx$ 60% lower than in water deficit stressed sugarcane of susceptible (e.g., LC 85-384) and resistant (e.g., HoCP 85-845) cultivars but oviposition preference and levels of injury to stalks relative to each cultivar did not change (*i.e.*, HoCP 85-845 had 44% less injury than LCP 85-384 within each irrigation regime) [68,70]. Under controlled greenhouse conditions, well-watered sugarcane plants had 82.8% to 90.2% fewer *E. loftini* eggs on them than water deficit stressed plants, larval entry holes on stalks were 44.4% to 94.5% less abundant, and adult exit holes were reduced by 64.3% to 88.9% [69]. Although *E. loftini* prefers to deposit its eggs on dry leaf tissue, living sugarcane leaf tissue of water deficit stressed plants might attract more egg laying females than nonstressed plants because of the heightened concentrations of nutrients, such as free amino acids that are essential for insect growth and development to adulthood [69,70]. It is possible that dry leaf tissue might serve as a cue for *E. loftini* females to oviposit on plants with relatively high accumulations of nutrients beneficial to the resulting larvae [54,69]. Water deficit in nonirrigated field plots increased accumulations of free nonessential amino acids aspartic acid, proline, serine, and tyrosine, and essential amino acids histidine, isoleucine, and methionine and intensified pressure from *E. loftini* occurred in those plots [70]. Another field study showed that elevated levels of free methionine and aspartic acid in sugarcane were associated with oviposition preference by *E. loftini* [68]. Water deficit in a greenhouse without confounding factors common to field situations induced a substantially wider range and less variability of free amino acid accumulations than were detected in field-grown sugarcane [69]. Drought stress elevated accumulations of free glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tyrosine, valine, total free essential amino acids in three repeated bioassays (in two of the bioassays, free alanine also increased) on two cultivars (Table 1 shows data for one of the three bioassays) [69]. In addition to free amino acids, fructose has also been associated with oviposition preference and injury to sugarcane stalks [92,93], but water deficit stress has not yet been evaluated for its effects on fructose concentrations.

**Table 1.** Mean ( $\pm$  SE) picomoles of free amino acid per microliter of sugarcane stalk juice in two cultivars, L 97-128 and CP 70-321, that were well watered or drought stressed in a greenhouse [69].

Free Amino Acids <sup>a</sup>	Treatment <sup>b</sup>			
	L 97-128 W	CP 70-321 W	L 97-128 D	CP 70-321 D
Alanine	3560 $\pm$ 193 b	5836 $\pm$ 1324 b	12,257 $\pm$ 1423 a	7857 $\pm$ 2277 ab
Arginine	1436 $\pm$ 185 a	677 $\pm$ 52 b	1084 $\pm$ 93 a	855 $\pm$ 35 a
Aspartic acid	2074 $\pm$ 158	2827 $\pm$ 233	2516 $\pm$ 61	2118 $\pm$ 311
Glutamic acid	18 $\pm$ 18 b	7 $\pm$ 7 b	126 $\pm$ 43 a	860 $\pm$ 8 a
Glycine	396 $\pm$ 52 b	505 $\pm$ 37 b	623 $\pm$ 83 ab	653 $\pm$ 173 a
Histidine	598 $\pm$ 85 b	577 $\pm$ 77 b	1642 $\pm$ 218 a	1995 $\pm$ 273 a
Isoleucine	605 $\pm$ 57 b	565 $\pm$ 54 b	1293 $\pm$ 204 a	2858 $\pm$ 47 a
Leucine	441 $\pm$ 79 b	510 $\pm$ 52 b	776 $\pm$ 23 a	2639 $\pm$ 88 a
Lysine	367 $\pm$ 94 b	375 $\pm$ 57 ab	650 $\pm$ 80 ab	514 $\pm$ 65 a
Methionine	225 $\pm$ 20 b	239 $\pm$ 64 b	771 $\pm$ 88 a	1241 $\pm$ 168 a
Phenylalanine	258 $\pm$ 43 b	226 $\pm$ 49 b	908 $\pm$ 88 a	1008 $\pm$ 88 a
Proline	558 $\pm$ 36 b	518 $\pm$ 99 b	1198 $\pm$ 89 a	4062 $\pm$ 51 a
Serine	2306 $\pm$ 285 c	4315 $\pm$ 623 b	4468 $\pm$ 913 b	8875 $\pm$ 931 a
Threonine	1490 $\pm$ 95 b	2258 $\pm$ 192 ab	2954 $\pm$ 444 a	3887 $\pm$ 510 a
Tyrosine	209 $\pm$ 24	186 $\pm$ 26	357 $\pm$ 84	515 $\pm$ 60
Valine	1193 $\pm$ 260 b	1563 $\pm$ 30 ab	2797 $\pm$ 502 a	5584 $\pm$ 259 a
Essential amino acids <sup>c</sup>	6616 $\pm$ 145 b	6992 $\pm$ 68 b	12,878 $\pm$ 1472 a	20,585 $\pm$ 983 a
Total	15,749 $\pm$ 540 c	21,189 $\pm$ 2108 bc	24,424 $\pm$ 2837 b	45,528 $\pm$ 2656 a

Means within each row followed by different letters are significantly different ( $p < 0.05$ ), one-way ANOVA, randomized complete block design, df = 3,12; <sup>a</sup> Cystine was detectable but not found in the samples;

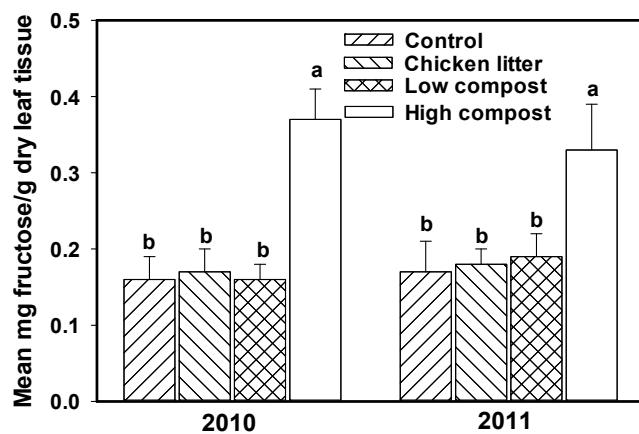
<sup>b</sup> W, well watered; D, drought stressed; <sup>c</sup> Comprised of arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, and valine.

In regions of relatively low rainfall and in regions that experience periods of drought, sugarcane should be adequately irrigated to avoid exacerbating *E. loftini* infestations [14,66,69,70,94,95]. The eldana borer, *Eldana saccharina* Walker (Pyralidae), a stalk boring lepidopteran pest of sugarcane and other gramineous crops in Africa [96–99], responds to some environmental stimuli much like *E. loftini* [14]. Drought stress, for example, is associated with severe *E. saccharina* infestations [99–102] and *E. saccharina* numbers have been reported to decrease in response to rainfall [103]. Larval growth of *E. saccharina* is more rapid and more robust in water deficit stressed sugarcane than in well-watered plants. Hence, African sugarcane growers are advised to keep their sugarcane fields adequately irrigated [100,104,105].

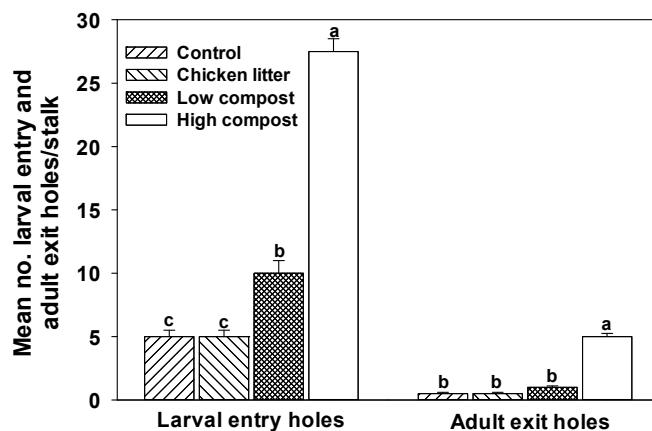
### 3.2. Soil Nitrogen

Nutrient-poor soils are a source of plant stress which is often ameliorated by applying fertilizers. Relatively high soil nitrogen concentrations in forms that are assimilated by plants can augment the nutritional value of species that host chewing and sucking herbivorous arthropods [106–110]. In this way, rich or excessive soil nutritional quality can exert stress by increasing the intensity of pest infestation. High soil nitrogen, for example, affects the degree to which sugarcane is infested and injured by *E. loftini* [93]. In field plots located in the Lower Rio Grande Valley, organic matter with 1.1% N (3320 ppm nitrate) applied at relatively low and high rates 8 mo before planting resulted in 2.6- to 4-fold more soil nitrate at planting time than noncomposted soil [93]. The recommended rate of nitrogen fertilizer for Lower Rio Grande Valley sugarcane was applied at the beginning of two consecutive growing seasons. Sugarcane leaf tissue from the heavily composted plots contained substantially more nitrogen than leaf tissue from low compost and noncomposted control plots [93]. Leaf tissue from plants grown on heavily composted soil during the first growing season had significantly ( $p < 0.05$ ) more nitrogen than leaf tissue from the control [93]. Free arginine, histidine, and lysine, and total free essential amino acids and total (includes nonessential) free amino acids were in greater abundances in leaves from the heavily composted plots than in leaves from the other treatments [93]. Further, fructose was  $\geq 2.2$ - and  $\geq 1.7$ -fold more abundant in sugarcane grown on

heavily composted soil than on the other plots (glucose and sucrose concentrations were not affected) during the plant and ratoon growing seasons, respectively (Figure 2) [93]. Numbers of larval *E. loftini* entry holes and adult exit holes in sugarcane stalks were  $\geq 2.3$ -fold and  $\geq 2$ -fold greater, respectively, in heavily composted plots than in the other plots (Figure 3) [93]. The enhanced nutritional value of sugarcane plants increases production of *E. loftini* adults which contributes to the magnitude of the next generation and the amount of injury to the crop. The association of host plant vulnerability to *E. loftini* and fructose concentrations suggests that the sugar, which occurs in relatively low concentrations, might be a limiting nutritional factor for the pest [92]. Although sugarcane stools (clumps of stalks) grown in the heavily composted plots were comprised of 18% more stalks than in the other treatments during the first growing season, that increase was more than offset by intensified *E. loftini*-induced injury [93]. Stalks in the low compost and control plots were 16% and 31% heavier, respectively, than in the high compost plots [93].



**Figure 2.** Mean ( $\pm$ SE) mg/g dry weight of fructose found in leaves of sugarcane, maize, and sorghum; different letters over bars within each type of sugar indicate significant differences ( $p < 0.05$ ) [93].



**Figure 3.** Mean ( $\pm$ SE) numbers of *E. loftini* larval entry holes and adult exit holes in sugarcane stalks grown on field plots amended with chicken litter, or low (102,306 kg/ha) and high (306,916 kg/ha) amounts of compost, and in non-amended control plots, 2011, Hidalgo Co., TX; letters over bars for each type of hole indicate significant differences ( $p < 0.05$ ) [93].

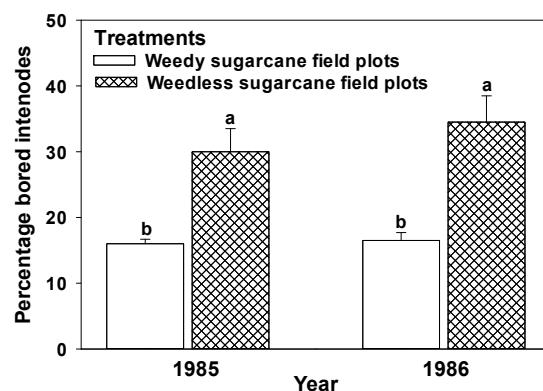
In addition to being similarly affected by water deficit stressed sugarcane plants, *E. saccharina* injury to sugarcane in Africa is exacerbated by heavy use of nitrogen fertilizer [14,104,111]. Moderate nitrogen fertilizer application is recommended in South Africa to avoid intensifying *E. saccharina* infestations [104,111] particularly during periods of drought [105]. In areas where *E. loftini* is problematic in sugarcane, growers should also apply nitrogen fertilizer judiciously [14,93].

## 4. Biotic Environmental Stress Factors

### 4.1. Weed Growth

Weed growth exerts a variety of effects on the ecology of sugarcane fields [94], the most obvious being competition with the crop. Infestations by weeds, especially perennials like johnsongrass, can cause substantial economic losses [112–114] of up to 84% [115]. Weeds compete more effectively against sugarcane than many short-season row crops to an extent because of sugarcane's relatively wide row spacing ( $\approx 1.8$  m) and slow seedling growth [116]. Less competitive annual weed species die back when the sugarcane canopy closes overhead [22,117], but uncontrolled annual summer weeds have been associated with reductions in sugarcane stalk density, biomass, and commercial sugar production of up to 24%, 19%, and 15%, respectively [22]. While weeds are clearly stress factors under many circumstances, in wet environments (e.g., southern Louisiana) they are not as likely to create conditions of water deficit stress in sugarcane [94] as they are to compete for sunlight during the early part of the growing season. After the sugarcane canopy closes, excluding enough sunlight to kill annual weed undergrowth, the dense mat of dry vegetation becomes a mulch that conserves soil moisture (low free proline levels in the sugarcane indicate absence of water deficit stress [118]) [119]. In the drier Lower Rio Grande Valley, weeds might compete for water as well as for space and light when the sugarcane is young. It is possible that weeds are more likely to affect sugarcane physiochemistry in south Texas in ways that increase infestation by *E. loftini* than in wetter environments.

While many weed species are alternate hosts to phytophagous nematodes [119], pathogens of sugarcane [94], and *D. saccharalis* and *E. loftini* [14], weeds have also been shown to facilitate the reduction of damage inflicted by *D. saccharalis* (Figure 4) [120–122]. Predation can be a decisive factor against *D. saccharalis*, particularly in wet or moist regions where red imported fire ant, *Solenopsis invicta* Buren, populations flourish [22,123]. Using stable-activable rare earth elements as tracers to mark (presumably monogyne) *S. invicta* colonies, Showler *et al.* [122] determined that the discrete foraging territories [120] are substantially smaller in weedy sugarcane plots, permitting denser colonization and that resulted in 60% less *D. saccharalis* injury to sugarcane stalks than in sugarcane field plots devoid of weed growth. In terms of the natural enemy complex, Louisiana sugarcane fields infested with monocot, dicot, and a mix of both were more diverse in terms of soil surface- and foliage-associated arthropods, including natural enemies of *D. saccharalis*, than bare-soil systems [117]. Sugarcane systems in Louisiana support  $\geq 84$  species of spiders, important egg predators of *D. saccharalis* [124], in 18 families [125] and spider diversity and abundances are increased by weed growth in sugarcane fields [22,126–128]. Anthocorids, nabids, reduviids, earwigs, carabids, various wasps, and other natural enemies of *D. saccharalis* have also been reported to be more numerous in weedy sugarcane habitats than where weeds have been eliminated [22,121].



**Figure 4.** Mean ( $\pm$ SE) percentages of sugarcane internodes bored by *Diatraea saccharalis* in weedy and weedless sugarcane field plots at harvest during two growing seasons, Assumption Parish, Louisiana; significant ( $p < 0.05$ ) differences are indicated by different letters over the bars [22].

Conservation of weeds along field borders has been suggested for maintaining populations of a parasitic tachinid fly, *Lixophaga sphenopheri* (Villen.), which attacks the New Guinea sugarcane weevil, *Rhabdoscelus obscurus* Boisd., in Hawaii [129]. Because uncontrolled weed growth is often deleterious, limited weed habitat “islands” within sugarcane fields [117] or confining weeds to furrows with early season weed control only on the row tops might be ways of conserving *S. invicta*, spiders, and other arthropods that parasitize and consume *D. saccharalis* [22].

A preliminary report suggests that *S. invicta* might prey on *E. loftini* [130], hence, vegetational diversification using weeds might enhance populations and diversity of natural enemies [14,53], reducing injury much in the same way as *S. invicta* can for *D. saccharalis*. In the dry Lower Rio Grande Valley, however, rank weed growth in cotton did not result in elevated numbers of *S. invicta* [131] which reaches higher densities in wetter regions such as southern Louisiana [123]. Therefore, in the Lower Rio Grande Valley, weed conservation with the aim of increasing natural enemy populations might not be particularly effective.

#### 4.2. Greenchop Leaf Residue

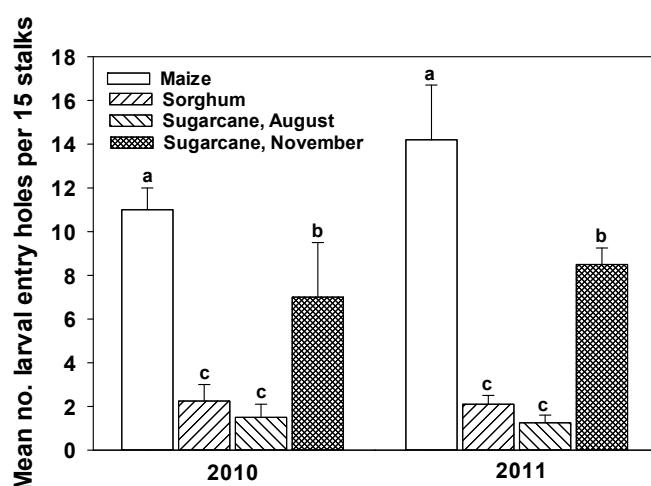
The common practice of burning the leaves off the stalks of sugarcane just before harvest pollutes the air, results in adverse health effects [132–134], and can cause deterioration of soil structure and loss of organic matter and nutrients [135,136]. Sometimes the leaves are instead stripped from the stalks, often cut into small pieces and left as a 15–20-metric ton/ha mat of “greenchop” covering the soil surface [137] 8–10 cm deep [37,138]. While greenchop mulch has been reported to improve sugarcane yield [139–143], it can also immobilize N and P [144,145], inhibit uptake of soil N under certain conditions [146,147], and, presumably because of the induced stress, reduce tillering [148] and yield [149]. Planting season sugarcane stalks harvested in the Lower Rio Grande Valley had 2.3- and 2.8-fold more *E. loftini* entry holes per stalk in field plots where greenchop was left on the soil surface as a mulch and where greenchop was mechanically incorporated 20 cm into the soil, respectively, than in plots without greenchop [150]. During the same growing season, percentages of *E. loftini*-injured internodes per stalk were 2.3- and 2.6-fold higher in plots with greenchop mulch and soil-incorporated greenchop, respectively. Statistically significant effects of greenchop, however, did not occur during the ratoon season [150]. Although greenchop can induce stress to sugarcane by interfering with soil nutrient availability, the difference in *E. loftini* damaged internodes did not occur as a result of elevated nitrogen and free amino acids. It is possible that the greenchop, which dries in the field, itself attracted *E. loftini*.

#### 4.3. Proximity to Susceptible Maize

Crops that are vulnerable to *E. loftini* can serve as reservoirs for the pest which, on moving into the sugarcane, intensifies stress to the plants from larvae already tunneling within stalks. Where sugarcane and maize are grown (along with other crops) as a patchwork agricultural landscape, such as the Lower Rio Grande Valley, *E. loftini*-susceptible maize, preferred over sugarcane [51,52], can accumulate the pest until the maize is harvested and the adults move into sugarcane [52]. Three months after August harvest of maize in the Lower Rio Grande Valley, larval entry holes in November-harvested sugarcane stalks (sugarcane in south Texas is usually harvested November–December) had increased by 7- to 8-fold (Figure 5) [52]. Tactics that might help to reduce movement of *E. loftini* from harvested maize into sugarcane include growing *E. loftini*-resistant maize cultivars near sugarcane and avoiding *E. loftini* susceptible maize cultivars [52].

Two transgenic *Bt* maize varieties (registered for use against a number of lepidopterous pests but not *E. loftini*, Table 3) were demonstrated to exhibit resistance against *E. loftini* injury in the Lower Rio Grande Valley compared with two maize cultivars lacking resistance to lepidopteran pests (Table 3) [151]. One of the two resistant cultivars, Pioneer 31G71, decreased losses of entire stalks from lodging and fungal rot by 60% and reduced numbers of larval entry holes by 41% [151]. The other resistant cultivar, Golden Acres 28V81, reduced stalk loss by 94.6% and entry holes by >99% [151].

Numbers of larval entry holes in Pioneer 31G71 were not statistically lower than in non-*Bt* control cultivars [151], and because the cultivar was associated with a <70% decline in adult emergence, it is not a notably effective trap crop for suppressing *E. loftini* injury to nearby sugarcane (Table 4). On Golden Acres 28V81 stalks, however, no adult exit holes were observed [151]. An ideal dead end trap cultivar for a stalk boring pest will be more attractive than susceptible cultivars, and stalks will be less prone to shattering, lodging, and stalk rot diseases, extending their capacity to continue trapping through its growing season [14] while curtailing adult emergence to the extent achieved by Golden Acres 28V81. In the same vein, a *Bt* Cry1Ab maize cultivar that decreased survival of *D. saccharalis* to nearly zero was suggested to be a trap crop for that pest [112]. Golden Acres 28V81 was almost completely resistant to larval *E. loftini* boring (Table 4) [151]. Whitish larval feeding “tracks” scarred the outermost tissue of Golden Acres 28V81 without penetrating the stalk, suggesting antibiosis as the basis of resistance [151]. Hence, Golden Acres 28V81 is a potentially suitable trap plant for *E. loftini* eggs with negligible risk to the stalk [151]. Growing a transgenic maize variety like Golden Acres 28V81 with high biocidal activity against *E. loftini* within agricultural landscapes intermingled with sugarcane fields might be the best way of “deploying” maize as a dead end trap crop to protect sugarcane. For many years it has been recommended that growers plant sugarcane as far away as possible from maize, but the role of transgenics in stalk borer management might change that practice. Resistance management, however, could remain an issue [152].



**Figure 5.** Mean ( $\pm$ SE) numbers of *E. loftini* larval entry holes in maize, sorghum, and sugarcane on the harvest date for maize and sorghum (in August) and in sugarcane on the harvest its date (in November), field plot assay, Hidalgo Co., TX, USA; different letters over bars within each year indicate significant differences ( $p < 0.05$ ) [52].

**Table 2.** *Bt* maize varieties and the pests against which they are registered [151].

Pests		
Variety and Active Gene	Common Name	Scientific Name
Pioneer 31G71 HX1 gene	black cutworm	<i>Agrotis ipsilon</i> Hufnagel
	corn earworm <sup>a</sup>	<i>Heliothis zea</i> (Boddie)
	European corn borer	<i>Ostrinia nubilalis</i> Hübner
	fall armyworm	<i>Spodoptera frugiperda</i> J.E. Smith
	lesser corn stalk borer	<i>Elasmopalpus lignosellus</i> (Zeller)
	southern corn stalk borer	<i>Diatraea crambidioides</i> (Grote)
	southwestern corn borer	<i>Diatraea grandiosella</i> Dyar
	sugarcane borer	<i>Diatraea saccharalis</i> (F.)
	western bean cutworm	<i>Loxagrotis albicosta</i> Smith

**Table 3.** *Bt* maize varieties and the pests against which they are registered [151].

Pests		
Variety and Active Gene	Common Name	Scientific Name
Golden Acres 28V81 VT3Pro gene	corn earworm <sup>a</sup>	<i>Heliothis zea</i> (Boddie)
	corn rootworm	<i>Diabrotica</i> spp.
	European corn borer	<i>Ostrinia nubilalis</i> Hübner
	fall armyworm	<i>Spodoptera frugiperda</i> J.E. Smith
DKC 69-72 (non- <i>Bt</i> )	none	
BH Genetics 9050 (non- <i>Bt</i> )	none	

<sup>a</sup> “Suppression” only.

**Table 4.** Mean ( $\pm$ SE) numbers of internodes and *Eoreuma loftini* damage per corn stalk,  $n = 5$  stalks/plot, Hidalgo County, TX, USA, 18 July 2011 [151].

Cultivar <sup>a</sup>	No. Internodes Per Stalk	No. Bored Internodes Per Stalk	No. Larval Entry Holes Per Stalk	No. Adult Exit Holes Per Stalk
9050	13.0 $\pm$ 0.1	2.28 $\pm$ 0.25	5.12 $\pm$ 0.34 a	1.40 $\pm$ 0.21 a
69-72	13.0 $\pm$ 0.01	2.15 $\pm$ 0.21	4.82 $\pm$ 0.78 a	1.38 $\pm$ 0.17 a
31G71	13.1 $\pm$ 0.1	1.30 $\pm$ 0.44	2.52 $\pm$ 0.89 ab	0.45 $\pm$ 0.20 b
28V81	13.0 $\pm$ 0.1	0.02 $\pm$ 0.02	0.05 $\pm$ 0.05 b	0 b
F <sup>b</sup>	0.47	12.61	11.96	14.41
P	0.7094	0.0001	0.0001	<0.0001

Means within each column followed by different letters are significant ( $p < 0.05$ ), Tukey's HSD; <sup>a</sup> BH Genetic 9050 (non-*Bt*), DKC 69-72 (non-*Bt*), Piorneer 31G71 (*Bt*), Golden Acres 28V81 (*Bt*); <sup>b</sup> df = 3, 31.

## 5. Conclusions

Environmental stress factors for sugarcane that influence the severity of stalk borer infestations arise from a variety of abiotic and biotic causes, including the stalk borers themselves. Some stress-inducing factors can alter the sugarcane agroecosystem and the plant's physiochemistry sufficiently to influence stalk borer survival and preference or non-preference for affected plants, substantially enhancing or diminishing yield. Grower practices that alter plant physiochemistry, such as irrigation and applying moderate rates of fertilizer in areas with *E. loftini* pressure, can induce degrees of crop resistance against the pest. The biochemical changes associated with some of the factors are probably not limited only to those that are reported here. Fructose concentrations, for example, should be measured in response to water deficit stress, and other nutrients as well as secondary compounds that might govern interactions with herbivorous arthropods. Other factors, such as weed growth, can conserve relatively large numbers of herbivorous prey arthropods that support larvae and diverse populations of natural enemies. When stalk borer injury is considered to be a stress factor, prudent choice of nearby crops can reduce the threat of increased stalk borer injury to the sugarcane.

Although the two most important stalk borer species in the United States, *D. saccharalis* and *E. loftini*, are both in the family Crambidae, their behaviors and environmental preferences are sufficiently different from each other to be affected by environmental factors in ways unique to each species. All of the factors described in this review can be neutralized or manipulated to reduce stalk borer injury to sugarcane through adoption of appropriate cultural practices. In the instance of *D. saccharalis*, noncompetitive weed growth might be permitted to increase natural enemies that reduce populations of the pest, and susceptible maize cultivars should not be grown near sugarcane. For *E. loftini* management, adequate irrigation, judicious application of fertilizer, planting away from susceptible maize, using trap crops, and possibly adopting a different harvest-time leaf removal method should be considered.

The physiochemical and physical changes in sugarcane plants associated with water deficit stress and soil richness offer important clues for breeders. Sugarcane cultivars that are drought tolerant accumulate relatively low concentrations of certain nutrients (e.g., free essential amino acids and fructose), and that have leaves that do not curl on drying will probably have moderate to strong resistance against *E. loftini*.

As *E. loftini* populations increase further in Louisiana's sugarcane producing region, and possibly in sugarcane of southern Florida, it is not yet clear whether the species will predominate (or perhaps both species will co-exist in relatively large numbers) over *D. saccharalis* in regions wetter than south Texas. The examples of how environmental factors interact with sugarcane pests are only a part of a much broader agricultural mosaic involving a wide array of different climates, crop and weed species, pest and natural enemy complexes, growing practices, and pest management strategies. Deeper understanding of how environmental factors are related to plant-insect interactions will reveal new cultural practices and plant resistance factors that can be incorporated into integrated pest management strategies.

**Conflicts of Interest:** The authors declare no conflict of interest.

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