

## **Literature Review**

### **Double-cropped corn**

#### **Rationale for double-cropped corn in Virginia**

In 1997, researchers in Virginia began conducting experiments to evaluate the potential of a late-planted corn crop for grain following the harvest of a small grain (Brann, 1997). In Virginia, the primary constraint to full season corn production is the availability of sufficient moisture during the periods of pollination and grain filling. Historical precipitation and evapotranspiration data suggest that late-planted corn can have a higher probability of moisture during these critical periods of development (Virginia State Climatology Office, 1997). An additional advantage of double-cropped corn is the reduced risk of crop failure, as two crops would be harvested in one growing season. Double-cropped corn is intended to provide Virginia growers with an additional option in their choice of cropping systems.

Double-cropped corn is a new cropping system for Virginia and management practices requires research in order to provide growers with the proper information to maximize returns. Delayed planting shifts the development of the corn plant to later in the season, exposing the corn crop to different insect, weed, and pathogen populations as compared to full season corn. In some cases, delayed planting may help avoid certain pests. For example, overwintering larvae of corn rootworm, seedcorn maggot, and annual white grubs may exhaust their resources and die, or as in the case of the annual white grub complex, complete development of the injurious larval stage and enter pupation

before the corn crop is planted (Youngman and Tiwari, 2004). However, other pests may pose problems in late planted corn due to increased pest populations or because the timing of the initial incidence occurs when the plant is more susceptible. For example, common maize rust (*Puccinia sorghi*) was more severe in late-planted corn than in full season corn in 1997 (D. Brann, personal communication). Older corn tissue is generally resistant to *P. sorghi* (Shurtleff et al., 1980), but when spores are blown in with summer storms from the tropics, the late-planted corn is still young and susceptible enough for disease development. European corn borer may be especially damaging to double-cropped corn, since the susceptible stages of crop growth more closely coincide with the second generation of European corn borer populations. Double-cropped corn may face numerous other biological constraints due to insects, diseases, and weeds.

Double cropping of corn for grain following the harvest of a small grain is a strategy utilized by a relatively small number of farmers in eastern Virginia. More commonly, a late planting or double-crop of corn is planted for silage by farmers throughout Virginia. Late planted corn for grain can be a viable option for farmers with a suitable growing season length. Furthermore, Behl et al. (1997) suggest that soils that are too droughty to produce only a summer crop profitably could benefit from a continuous double-cropping rotation that emphasizes a winter annual crop.

### **Double-cropped corn hybrid trials**

Three years of double-cropped corn trials by Behl et al. (1997) in eastern Virginia are summarized. In 1997, hybrid trials indicated that acceptable yields could be obtained with double-cropped corn in eastern Virginia under irrigated and non-irrigated conditions.

Of 20 hybrids in the trial, the top 5 hybrids irrigated and the top 6 hybrids non-irrigated were Bt hybrids. This trend continued in the 1998 double-cropped corn trials at Corbin Hall, Virginia where four of five of the top yielding hybrids were Bt hybrids. In 1999, field trials conducted in New Kent County, Virginia performed well in terms of grain yield and quality, whereas non-Bt hybrids were very poor in quality due to insect and bird damage. After three years of trials in eastern Virginia, it was recommended that for corn planted in mid- to late-June in eastern Virginia, it is almost always beneficial to plant an insect resistant hybrid.

## **Major insects and diseases in corn production**

### **European corn borer**

The European corn borer (*Ostrinia nubilalis*) can cause extensive yield losses and control expenditures annually in corn, vegetables, cotton and sorghum in the United States (Mason et al., 1996). European corn borer damage on young corn causes greater yield losses relative to damage initiated at later stages of plant development (Mason et al., 1996). The damage and yield loss result from leaf and midrib feeding, stalk tunneling, leaf sheath and collar feeding, and ear damage leading to broken stalks, smaller ears, and dropped ears (Mason et al., 1996). In addition to causing direct yield losses, European corn borers are associated with certain stalk rots and ear rots in corn. Ear rots can be especially devastating to the quality of grain due to mycotoxin contamination (Shurtleff, 1980).

European corn borers can have up to four generations in a year, depending on the regional climate and duration of the growing season. In Virginia, there are typically two or three generations per year (Youngman and Tiwari, 2004). First and second generation European corn borers damage corn leaves in the whorl stage, while the second and third generation feed on ears and stalks, although this varies with the planting date of the corn. It is the later generations that are associated with ear rots in corn.

European corn borers open potential infection sites for pathogens by wounding corn, serve as a possible vector by introducing fungi to the wounds, and decrease the overall vigor of the plant (Jarvis et al., 1984). Wounds may be colonized by fungal inoculum, which is ubiquitous in the environment and dispersed by wind, rain, and insects.

### **Stalk Rots**

Stalk rots cause major losses in corn production by restricting the flow of water and nutrients and by increasing stalk lodging (Shurtleff, 1980). The most common fungal stalk rots, often occurring simultaneously, are caused by *Fusarium* species (teleomorph=*Gibberella*), *Diplodia*, *Colletotrichum*, and also include the charcoal rots (Jugenheimer, 1976). Many different stresses predispose corn to stalk rots including unbalanced soil fertility, drought, soil saturation, dense planting populations, foliar diseases, insect damage, hail damage, disease, and other environmental stresses. When a corn plant develops a root rot, it is nearly always followed by some degree of stalk rot. Thus, stalk rot pathogens can also enter through the roots.

An association between European corn borer damage and stalk and ear rots has been well known for some time (Christensen and Schneider, 1950). The scientific literature has only recently shown that a true vector relationship exists between European corn borers and the fungi causing ear rots, while the vector relationship to the stalk rots remains unclear (Munkvold, 1998). Stalk rot fungi have been isolated from the surface of European corn borer larvae repeatedly and stalk tunnels are a potential site for infection. However, some studies have shown that stalk rot may not develop despite inoculation with one or many of the stalk rotting fungi (Dodd, 1998). Many of the fungi, including *Fusarium* species are present at all times on the plant and in the field and are probably a part of the naturally occurring microflora of corn. Munkvold and Desjardins (1997) suggest that *Fusarium* can be considered an endophyte of corn.

Stalk rots may occur as a result of the stresses induced by European corn borers, and not so much due to the introduction of inoculum. Dodd (1998) observed that stalk rot only develops in corn when borers break the stalk above the ear, drastically reducing photosynthate from the upper leaves, and that no stalk rot occurs in stalks broken below the ear, although the ear is lost. A reduction in photosynthesis leads to the death of the roots and invasion by root and stalk rotting fungi. A similar relationship exists between reduced photosynthesis due to foliar diseases, followed by stalk death and cessation of grain filling. This view challenges the widely held view that borers primarily cause stalk rots in corn by providing an avenue for stalk rotting fungi to enter the plant.

Clearly, European corn borer can reduce photosynthate production in injured corn plants and may carry fungi with them. Even if insects are not the primary vectors of stalk rotting fungi, injured corn is lacking the structural defenses of an intact stalk and exposes

susceptible tissues to the environment. Regardless of the source of inoculum, injury by European corn borer is associated with an increased incidence of stalk rots and reduced yields in corn.

### **Ear rots**

There are a number of ear rots causing slight yield and quality losses in corn; however, the greatest consequence of ear rots caused by fungi is contamination of grain with mycotoxins. The most common ear rots containing mycotoxins are several species of *Fusarium*, *Penicillium*, and *Aspergillus flavus* (Shurtleff et al., 1980). Grain that is contaminated with excessive levels of mycotoxin is unsuitable for animal consumption (Shurtleff et al., 1980).

Insect injuries are common sites of *Fusarium* infection of corn ears. Inoculum is carried in by insects (mainly European corn borer and corn earworm), airborne, or rain dispersed. Kernel infection often occurs without insect damage, and the major infection pathways are through seed, stalk, and silks, with silks being the most common pathway for *Fusarium moniliforme* (Munkvold et al., 1997). No effective control practices have existed for ear rot and mycotoxin contamination until the recent release of transgenic corn hybrids expressing the Bt toxin for control of certain Lepidopteron insect pests, thus indirectly reducing these diseases.

### **Control of European corn borer induced disease**

Effective control measures for stalk and ear rots have been limited in the past. Recently, transgenic corn expressing Bt insecticidal toxins have reduced insect feeding

and provides a new strategy for reducing losses to insect damage and subsequent stalk and ear rots. In 1997, five unique Bt events were available to growers (Munkvold, 1998). In 2003, the Cry3Bb1 endotoxin was released in the U.S. for corn rootworm control. Additionally, the Cry1Fa2 endotoxin was released, which provides enhanced control of fall armyworm and black cutworm. Bt corn provides corn producers with an effective tool in the management of corn insects and diseases. Resistant insect populations are a threat to the use of Bt corn and strategies for resistance management are currently being considered (Youngman and Tiwari, 2004).

Prior to the advent of Bt corn hybrids, the best option for control of European corn borer was with chemical insecticide applications, the safest being Lorsban (chlorpyrifos) (Virginia Cooperative Extension, 1998). Bt corn is genetically engineered to express a gene from a soil bacterium, *Bacillus thuringiensis*, that codes for a protein toxin that is lethal to European corn borer and certain other lepidopteran insects. Since European corn borer and other insect pests injure corn and predispose it to stalk and ear rots, Bt corn may be effective in reducing levels of these diseases. Munkvold, Hellmich, and Showers (1997) have shown reduced levels of the fumonisins, a mycotoxin of *F. moniliforme*, in Bt hybrids compared to near isolines of non-Bt corn.

The level, duration, and specific site of Bt toxin expression in the corn plant vary with the different transformation events (Youngman and Tiwari, 2004). Those hybrids exhibiting full season expression, particularly in the kernels, may provide the best protection against ear rots (Munkvold et al., 1997).

The European corn borer has long been associated with stalk and ear rots of corn. European corn borers open infection sites, possibly serve as a vector for fungal pathogens,

and, perhaps most importantly, reduce the vigor of the plant. The extent of damage and disease induced by European corn borer greatly depends on the developmental stage of corn at the time of wounding, as well as many other environmental factors. The exact nature of the relationships between the insect and the fungal pathogens are still unclear in the case of stalk rots, whereas fusarium ear rot is frequently associated with European corn borer damage (Munkvold et al., 1997). For the first time, mycotoxins may be actively managed by hybrid selection. Bt corn hybrids provide a truly integrated approach to crop management by controlling some of the most damaging insect pests and subsequently reducing the occurrence of the associated stalk and ear rots of corn.

#### **Maize dwarf mosaic virus and maize chlorotic dwarf virus**

Maize dwarf mosaic virus (MDMV) and maize chlorotic dwarf virus (MCDV) occur worldwide and cause major losses in corn grown in the United States (Shurtleff et al., 1980). Several weed and crop species are capable of being infected by MDMV and MCDV; however the only overwintering host for these viruses is johnsongrass (*Sorghum halepense*) (Shurtleff et al., 1980). MDMV and MCDV are transmitted to corn primarily by insect vectors. Eberwine and Hagood (1995) demonstrated that postemergence johnsongrass control in corn increases the severity of MDMV and MCDV in corn due to the increased movement of insect vectors from dying johnsongrass to the corn crop. In double-cropped corn, an alternative cropping system currently under evaluation in Virginia, corn is planted no-till immediately after a harvest of small grains in June. Vector, weed, and virus populations may be greater at the time of planting for double-cropped corn as compared to full season planting dates for corn. It is hypothesized that

double-cropped corn will have an increased disease severity of MDMV and MCDV as compared to full season corn in the presence of johnsongrass, MDMV, MCDV, and vectors.

Maize dwarf mosaic virus and maize chlorotic dwarf virus are the two most economically important virus diseases of corn, often occurring together in the eastern United States (Gordon, 1976). Double infections result in the greatest amount of disease development and yield reductions (Shurtleff et al., 1980). There are different strains of MDMV, with MDMV-A being the strain that overwinters in the rhizomes of johnsongrass and is commonly found in Virginia (Eberwine, 1996). MDMV is a long, flexuous rod-shaped virion transmitted by aphids in a nonpersistent manner (Shurtleff et al., 1980). Aphid vectors, which are described below, may feed on infected johnsongrass and subsequently transmit the virus to corn.

The symptoms of MDMV are variable but typically include mosaic patterns or a mottling of the leaves and stunting and small ears may result from severe infections. Rosenkrantz and Scott (1978) reported that the highest disease incidence and yield loss occur when plants are inoculated at the five leaf stage, compared to plants inoculated at the three-, seven-, nine-, and eleven-leaf stages.

Maize chlorotic dwarf virus is an isometric virion, which overwinters in the rhizomes of johnsongrass (Shurtleff et al., 1980). It is transmitted from johnsongrass to corn in a semipersistent manner by leafhoppers. Symptoms caused by MCDV include chlorosis of young leaves, chlorotic striping or reddening of the leaves, and stunting in severe cases (Shurtleff et al., 1980).

## **Insect vectors of MDMV and MCDV**

Insect vectors are the most important method by which MDMV and MCDV are transmitted from johnsongrass to corn. There are at least 23 known vectors of MDMV including the corn leaf aphid (*Rhopalosiphum maidis*), the greenbug (*Schizaphis graminum*), and the green peach aphid (*Myzus persicae*) (Shurtleff et al., 1980). Under normal field conditions, aphids retain MDMV for up to six hours (Eberwine, 1996), although long distance aphid migration and extended periods of retention have been reported (Zeyen et al., 1987). MCDV is transmitted semipersistently by nymph and adult leafhoppers (*Graminella nigrifrons* and *G. sonora*) (Shurtleff et al., 1980) and virus transmission may occur up to four days after the initial acquisition (Eberwine, 1996).

## **Johnsongrass**

Johnsongrass is a common weed problem of commercial corn production in Virginia. It is an aggressive perennial reproducing primarily by seeds, but vegetative reproduction through rhizomes is also common. Johnsongrass rhizomes provide the only overwintering reservoir of MDMV and MCDV (Shurtleff et al., 1980) in Virginia.

## **Factors influencing MDMV and MCDV in double-cropped corn**

Eberwine and Hagood (1995) demonstrated that postemergence johnsongrass control in corn increases the severity of MDMV and MCDV in corn due to the increased movement of insect vectors from dying johnsongrass to the corn crop. Due to a longer growing period before herbicide treatment, johnsongrass should be older and taller in

double-cropped corn as compared to full season corn. Therefore, more tissue would be present to serve as a source of virus inoculum and as a host for insect vectors.

The virus titer in the infected johnsongrass should also be greater due to the longer period of viral replication allowed by the delayed herbicide treatment. Furthermore, the MDMV titer of infected johnsongrass is reported to increase following an herbicide treatment with nicosulfuron or primisulfuron and this higher titer may increase acquisition of the virus by vectors (VanGessel and Coble, 1993). Finally, insect vector populations would also increase by the time herbicide is applied. A larger population could theoretically transmit a greater amount of virus from johnsongrass to corn.

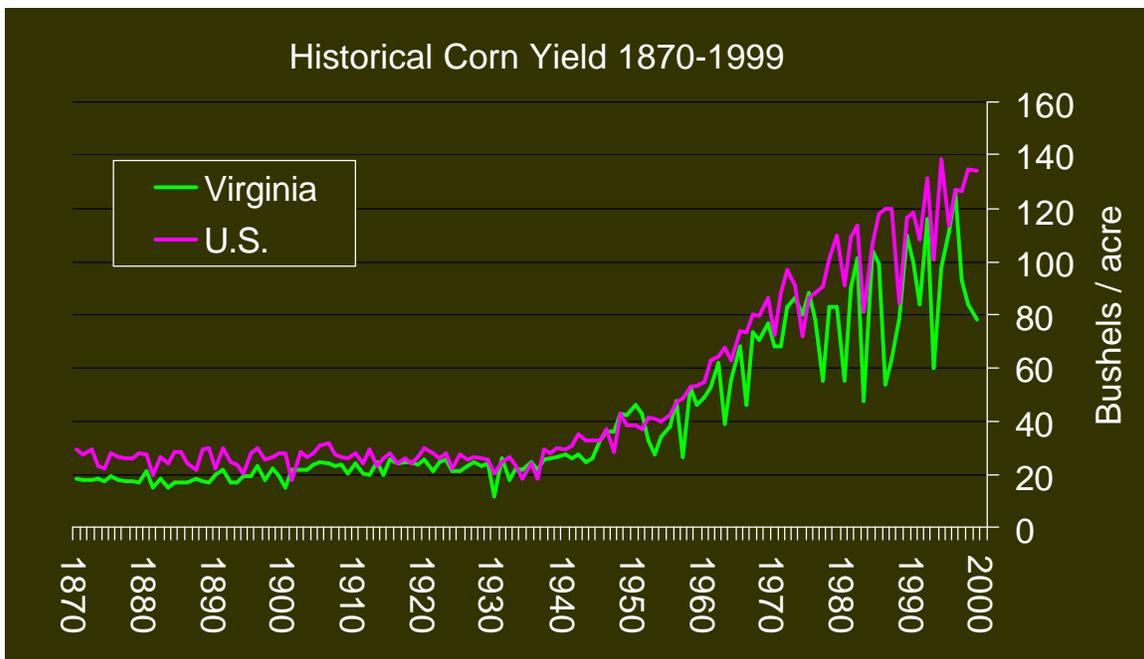
It is hypothesized that the late planting date for double-cropped corn may allow for increased populations of johnsongrass, aphids, MDMV, and MCDV, resulting in an increased disease severity of MDMV and MCDV in double-cropped corn as compared to full season corn. Johnsongrass treated with herbicide could take up to several weeks to die, thus facilitating the movement of insect vectors to the growing corn. This scenario is likely to occur only when all components of the disease cycle for MDMV and MCDV are present. In a double-cropped corn system, the small grain crop that is harvested prior to the planting of corn may suppress in-field johnsongrass infestations in some cases. In situations where the potential for MDM and MCD exists, resistant hybrids should be planted.

## Historical corn yields

Beginning in the mid-1930s, a relatively steady increase in corn yields is apparent (Figure 1). There are multiple factors contributing to this increase, including the introduction of double-cross hybrids in 1935 and single cross hybrids in the 1960s and 1970s. Fertility, pesticides, increased insect, disease and drought resistance and cold tolerance have also contributed to the trend. (Warren, 1998).

It appears that the variability of corn yields has dramatically increased since the mid 1970s in Virginia. It is hypothesized that the variability in these years may be explained by investigating the potential for drought, insect, disease, or other weather related factors in a good year (high yield) versus a poor year (low yield).

Figure 1. Historical corn yields 1870-1999 (Data from NASS).



## **The influence of weather at specific stages of corn development**

Drought stress at flowering results in an increased time interval between pollen shedding and silk emergence, also known as silk delay, loss of synchrony, or protandrous flowering. The anthesis-silking interval (ASI) is widely accepted as a measurement of the date when 50% of plants have visible silks minus the date when 50% of the plants have anthers exposed (Edmeades et al., 2000). ASI has a large impact on grain yield and this result has been demonstrated in Mexico (Bolanos and Edmeades, 1993), Canada (Dow et al., 1984), Europe, South Africa (DuPlessis and Dijkhuis, 1967), and the US (Jensen, 1971).

Hu and Buyanovsky (2003) demonstrated several useful approaches to modeling corn yield and climate in Missouri. They averaged annual plot yields at a long term (1895-1998) agricultural research site where management and rotation were consistent. They investigated the correlation of weather conditions with corn yields by placing each year into a category of either high, medium, or low yields. The within-season variation of temperature and precipitation was found to be correlated with corn yields, whereas average growing season conditions did not explain yield responses. Furthermore, they found that monthly averages were also insufficient to explain corn yields. A shorter time scale of temperature and precipitation pentads (a 5-day average) was sufficient to explain yield responses. Hu and Buyanovsky (2003) found that the major weather factors affecting yield depend on the development stage of the corn. Warm and dry weather conditions at planting were important for timely planting of the crop, and wet and cold conditions delayed planting. Freezing temperatures at germination injures seeds and seedlings. Dry conditions at germination may result in a larger root system as corn roots

grow downward to find available soil moisture. Warm and wet conditions during vegetative growth were found to be most favorable for corn yields. The conditions at silking to kernel fill indicated increased yields when conditions were cool and moist. Finally, the conditions at ripening may alter the rate of plant drying in the field.

Overall, scatter plots of time series from the long-term Missouri plots suggest an increase in variability of yields over time. Hu and Buyanovsky (2003) explain this as increased hybrid sensitivity to weather and climate. However, their analysis does not consider yield reducing insects, diseases, and weeds. Pests and diseases are very sensitive to weather conditions and the proposed response of crop yields to weather may be confounded by extrinsic factors.

The sensitivity of corn to weather has been studied by many researchers. Tollenaar (1971) suggested that grain numbers are determined in the period of 10 days before and 15 days after anthesis. Chang (1981) found that the period from six-weeks prior to silking to three-weeks after silking is the most critical stage for corn development in terms of heat and moisture stress. This is generally in agreement with Dale and Shaw (1965) and Runge (1968), who found the most sensitive stage of corn development was 25-days before to 15-days after silking, with one-week prior to silking being extremely critical. Chang (1981) determined that solar radiation during grain fill is the most important factor for yield.

### **Degree-day models for IPM**

Temperature is a driving force in many biological processes. Organisms such as plants, microbes, and insects do not generate their own heat and development is therefore

dependent on heat from the environment. A measurement of accumulated heat is often described as physiological time, expressed in degree-days ( $^{\circ}\text{D}$ ). Degree-days are widely used in the phenological examination of crop and pest interactions. An estimation of developmental stages can be calculated from accumulated degree-days from a specific starting point (biofix) and is frequently used in agriculture for plants, insects, and diseases. The timing of agricultural pest management decisions is more accurate when using a measurement of biological time in contrast to using calendar days. Accumulated degree-days can be used to estimate the growth stage of a crop and when susceptible stages of a pest occur, or when plant diseases or insect pests are likely to occur. More sophisticated models for estimating plant, insect, and disease phenology and timing incorporate additional environmental, management, or genetic factors.