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Adapting to Saltwater Intrusion: Profitability of Salt-Tolerant Soybeans in Eastern North Carolina

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In this edition of the *NC State Economist*, Greg Ferraro, Roderick M. Rejesus, Luke Gatiboni, and Andrea Gibbs explore the issue of saltwater intrusion and sea level rise (SWISLR) in Eastern North Carolina agriculture. First, general adaptation options to manage potential yield damage from saltwater intrusion are discussed. An analysis of the potential profitability impacts of using salt-tolerant soybean varieties is then described. In general, the use of salt-tolerant soybean varieties can help mitigate the potential profit-reducing impact of low-to-moderate levels of saltwater intrusion.

Introduction: Saltwater Intrusion and Sea Level Rise

There is growing evidence that saltwater intrusion and sea level rise (SWISLR) have caused substantial damage to coastal agriculture globally (Gibson et al., 2021; Kang et al., 2016). Five main factors typically drive the degree of saltwater intrusion and salinization observed on agricultural lands: (i) distance and elevation of sea surface level relative to the land and water table; (ii) the frequency and magnitude of storms and tides; (iii) the frequency and duration of drought; (iv) the level of water use (e.g., surface and groundwater withdrawals for drinking water and irrigation); and (v) hydrologic connectivity (e.g., tide gates, levees, agricultural diversions, roadside ditches, and canals) (Tully et al., 2019).

Note: Field impact from saltwater intrusion. Photo from Matt Ricker.

The state of Virginia, for instance, loses 474 acres (or 1.92 km^2) of farmland annually to SWISLR, mainly due to storm surges (Fagherazzi et al., 2019). Upland areas of all land types in the entire Chesapeake Bay region, including farmland, have likely seen 400 km^2 converted to wetlands over the last century due to sea level rise (Schieder, Walters, Kirwan, 2018). There are similar concerns for

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Note: Aerial view of field impacted by saltwater intrusion. Photo from Andrea Gibbs.

inundation and salinization for coastal and river-adjacent agriculture in Florida and California (Curtis & Schneider, 2011). North Carolina, on the other hand, is within a sea level rise "hotspot," where land submergence occurs 3-4 times faster than the global average (i.e., about 0.59 mm/year global average, compared to 1.97 mm/year for "hotspots" along the North American Atlantic coast, from 1950 to 2009) (Sallenger et al., 2012). Sea levels in coastal North Carolina cumulatively rose by 2.07–2.82 mm/year during the 20th century (NOAA, 2009), and may rise further by 0.3 m to 2.5 m depending on the frequency and magnitude of weather events moving forward (Sweet et al., 2017). For example, coastal Hyde County in North Carolina can face up to 1140 km^2 of agricultural salinization in the future, potentially endangering 4,200 people and $40 million worth of property (Davis et al., 2019). Bhattachan et al. (2018) predict that large areas of coastal Tyrrell County in North Carolina are also vulnerable to SWISLR-related soil salinization. They argue the Albemarle-Pamlico Peninsula region in North Carolina is particularly susceptible due to increased hydrologic connectivity from extensive agricultural drainage networks (Bhattachan et al., 2018).

A recent Public Broadcasting Service (PBS) report described the saltwater intrusion problem in the agricultural sector of Hyde County (PBS, 2023). In this coastal county, drainage canals are the main source of saltwater exposure. Canals help get water off farm fields, but these agricultural fields also become salinized as seawater intrudes inland from storm surges or onshore winds blow seawater toward the fields. The intruding seawater then penetrates the soil and adversely affects the productivity of crops grown in the fields – either by having considerably lower yields or the crops being unable to germinate (PBS, 2023). The soil in Hyde County is particularly susceptible to saltwater intrusion because of its high organic content, which binds to salt more strongly than sandier soil types. Tide gates can also help keep the water flow going seaward and prevent intrusions from regular tidal changes but are an imperfect solution due to their maintenance requirements and ineffectiveness against storm surges. Farmers near the coast think that the SWISLR problem is becoming worse, and they feel that they cannot simply abandon farmlands affected by SWISLR as is often suggested (PBS, 2023). This further

Note: Dike with pump drain attached (top) and floodgates (bottom) in Hyde County. Photo from Carl Crozier.

highlights the need for a variety of solutions and adaptation options for growers in coastal NC counties.

SWISLR Adaptation Options in Coastal Agriculture

Soil salinity negatively impacts crop yields and likely reduces revenue from agricultural production (Alkharabsheh et al., 2021; Kotuby-Amacher et al., 2000). Therefore, to maximize profitability, affected growers may consider the economic costs and benefits before investing in SWISLR adaptation measures. Short-term adaptation options include applying gypsum combined with a freshwater field flush, using deep tillage (Schneider et al., 2017), and/or changing the crop or crop variety planted (i.e., using more salt-tolerant crops or varieties). Long-term adaptation options to address SWISLR include the construction of protective structures, mechanisms for regular freshwater field flushing, and installation of floodgates in drainage zones to control saltwater inflow (NC State Extension, 2020).

The effectiveness of the mitigation and adaptation measures described above depends largely on the severity of the SWISLR problem faced by individual farmers. A report from the USDA suggests that commercial agriculture can recover from "sporadic salinity," which occurs due to episodic salt spray from ocean water, high tides, storm-driven flooding, saltwater intrusion during a drought, or saline irrigation water, with less intensive methods, such as field flushing. However, chronic and recurring salinity issues, which occur when saltwater intrusion begins to enter freshwater tables chronically or sea spray exposure increases sufficiently, may require more involved SWISLR mitigation and adaptation measures. For example, creating land easements that convert farmlands to marshlands (or wetlands) can be an effective strategy for addressing crop damage due to SWISLR (Gibson et al., 2021). Converting some coastal farmland to coastal marshland could separate productive farm fields from the ocean, providing a protective buffer from saltwater intrusion. However, it takes time for marshlands to develop (PBS, 2023), and this approach may not immediately address pressing SWISLR problems.

Other SWISLR adaptation measures, in combination with marshland development, can be employed to better address saltwater intrusion in coastal farms. In the presence of more chronic saltwater intrusion, growers can choose to plant different crops that are more tolerant to soil salinity or consider planting more salt-tolerant varieties of current crops. One way to measure the salinity of the soil, and then how well different crops perform at given levels of salt exposure, is through the electrical conductivity (EC) value of the soil. Previous research has identified EC thresholds indicating the level of salinity at which crops begin to see a yield reduction. These thresholds suggest that among the most common NC coastal row crops, cotton and wheat generally have the highest tolerance for salinity (thresholds of 7.7 EC and 6 EC, respectively) followed by soybean (threshold of 5 EC); corn is fairly salt intolerant (1.8 EC) (Gibson et al., 2021). For reference, non-saline soil has an EC of 0-2, slightly saline has an EC of 2-4, moderately saline has an EC of 4-8, strongly saline has an EC of 8-16, and extremely saline has an EC of over 16 (Gibson et al., 2021).

For farmers who wish to continue growing their current crops, another adaptation option is to use salt-tolerant crop varieties. For example, coastal soybean growers could consider planting salt-tolerant soybean varieties. However, before adopting these salt-tolerant varieties, it is important to examine their potential yields under various levels of saltwater intrusion severity, the potential costs, and ultimately their potential profit impact. In the next section, we explore these issues in more detail.

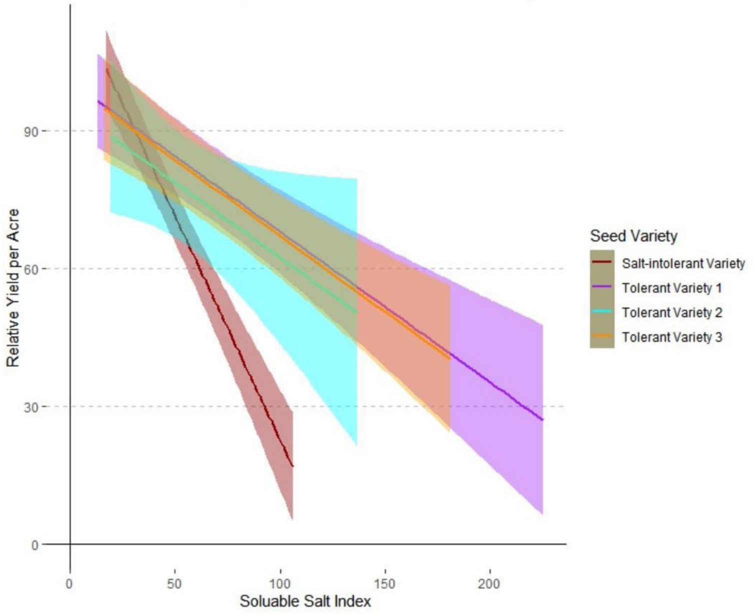
Economic Analysis: Potential Profitability Impacts of Salt-Tolerant Soybeans

Field Trial Data: Soybean Yields at Different Salt Levels in the Soil[1]

We utilize data from a one-year field trial (2021) in Eastern North Carolina to determine potential yield impacts of varying levels of saltwater intrusion when using: (i) a salt-intolerant soybean variety and (ii) three salt-tolerant soybean varieties.[2] Eight plots were planted of each variety and were naturally exposed to different levels of saltwater intrusion. The measure of saltwater intrusion (or salinity) used in the trial is the soluble salt index (SSI), which is based on the electrical conductivity (EC) analysis of the soil. Based on the work of Gibson et al. (2021), one can delineate the various levels of saltwater intrusion severity as follows: (i) non-impacted (SSI<33), (ii) sporadic salinity (33<SSI<53), (iii) recurring episodic salinity (53<SSI<93), (iv) low chronic salinity (93<SSI<173), and (v) high chronic salinity (SSI>173).

Results from the variety trials are summarized in Figure 1. Instead of actual yields (in bu./ac) in the y-axis, we use relative yields (%) where a 100% relative yield coincides with the highest yield for the variety considered. Hence, relative yield values below 100% reflect the yield from a particular plot in relation to the highest yield for that variety. For example, a 10% relative yield means that the yield from this plot is only 10% of the maximum yield for the variety planted in the plot. In general, Figure 1 suggests that soybean yields for both salt-intolerant and salt-tolerant varieties decrease as the level of saltwater intrusion increases. This indicates that, regardless of what variety is used, higher saltwater intrusion levels negatively affect crop yields and result in yield losses. However, the regression lines tend to be flatter for the salt-tolerant varieties than the salt-intolerant variety, indicating that yield damages at moderate-to-higher levels of saltwater intrusion tend to be smaller for salt-tolerant compared to salt-intolerant varieties. That is, for fields severely affected by saltwater intrusion, salt-tolerant soybean varieties will likely have lower yield losses due to salinity than salt-intolerant varieties. It is important to note that soybean yields for the salt-intolerant variety remain similar to the salt-tolerant varieties at low levels of saltwater intrusion.

Figure 1. Regressions of Relative Yield (%) on Soluble Salt Index (SSI) for Salt-Tolerant and Salt-Intolerant Soybean Varieties



Note: Authors' calculations based on field trial data. The graph describes how much yields fall as the soil salinity (indicated by the soluble salt index) increases. For example, as the soluble salt index reaches 100, the yields of the salt-intolerant variety (dark red line) fall to approximately 25% of their normal levels. Lines are the average relative yield and the color bands reflect the 95% confidence intervals.

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[1] Data from additional years of field trials are being collected. A more robust analysis with multi-year data will be conducted in the future.

[2] Due to confidentiality issues, we are not able to publicly report the actual soybean variety names and the companies that produced them.

NC Enterprise Budget: Price and Cost Data

To understand the economic implications of saltwater intrusion when using salt-intolerant and salt-tolerant varieties, one needs soybean price and input cost data corresponding to the field trial data set described above. We used the price and cost information (per acre) from the 2021/2022 soybean enterprise budget developed by North Carolina State University (NCSU) to analyze the potential profit impact of varying levels of saltwater intrusion. When necessary, we supplemented this enterprise budget information with estimates from the US Department of Agriculture - National Agricultural Statistics Service (USDA-NASS) for Hyde County, NC (since the field trial site is in Hyde County) or estimates at the national level, depending on availability. Information on the seed price for the different soybean varieties used in the trial was collected from a local seed supplier and these suppliers generally accept that one bag of seed is sufficient to plant one acre. The base cost and price information used in the analysis are presented in Table 1. One important thing to note in Table 1 is that the seed prices for the salt-tolerant varieties are only slightly higher than the salt-intolerant variety (an increased cost of $3.14 to $8.13/bag). We also assume that each seed type would provide the same yield absent salt exposure.

Table 1. Assumed Revenue and Costs, Soybeans (Per Acre)

Item	Base Costs & Revenues	Unit	Source of Information for Base Value
VARIABLE			
TRACTORS	$25.41	Index for price paid converted to $	NCSU
RENT	$94.50	Case, cropland – measured in $ / Acre	NASS (National data)
POTASH & PHOSPHATE	$38.81	Index for price paid converted to $	NCSU
LABOR	$23.06	Index for price paid converted to $	NCSU
INTEREST	$2.17	Index for price paid converted to $	NCSU
INSECTICIDES	$16.50	Index for price paid converted to $	NCSU (2023 value)
HERBICIDES	$31.59	Index for price paid converted to $	NCSU
FUNGICIDES	$23.55	Index for price paid converted to $	NCSU (2023 value)
SURFACTANT/ADJUVANT*	$3.58	5% of insecticides, insecticides, and herbicides	NCSU
LIME (USED P&P CPI)**	$17.99	Index for price paid converted to $	NCSU
FIXED			
HAULING	$10.40	$ - unchanged from NCSU base value	NCSU
SCOUT	$12.00	$ - unchanged from NCSU base value	NCSU
TRACTOR/MACHINERY	$54.67	$ - unchanged from NCSU base value	NCSU
SEED			North Carolina Seed Provider
— Non-Tolerant Variety	$52.47	Bag price	
—Tolerant Variety 1	$57.00	Bag price	
—Tolerant Variety 2	$60.60	Bag price	
—Tolerant Variety 3	$55.61	Bag price	
YIELD	53.20	BU / Acre	NASS (Hyde County, NC data)
PRICE	$13.20	$ / Acre, futures + basis	NASS (Hyde County, NC data)

Note: "NCSU" means that the information is from North Carolina State University. "NASS" means that the information is from the USDA National Agricultural Statistics Service (USDA-NASS).

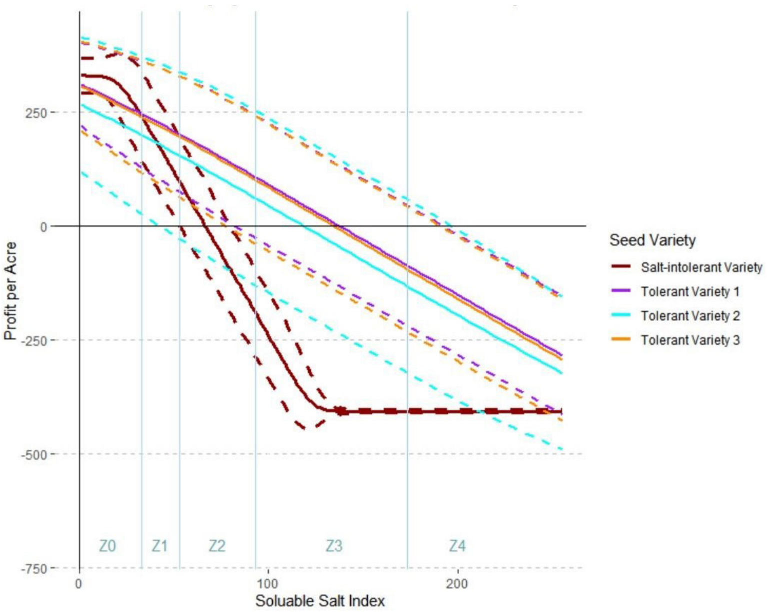
Using the field trial data and the enterprise budget data, as well as estimated distributions of the revenue and cost from NASS data, we conducted a simulation analysis to estimate the potential profit impact (in 2021 dollars) of varying levels of saltwater intrusion when using salt-intolerant and salt-tolerant soybean varieties. This approach allows us to estimate the profit impacts and calculate a 95% confidence interval around these profit impact estimates. The confidence interval is a range around our estimates that accounts for uncertainty and imprecision in the analysis.

Specifically, we generate these confidence intervals by modeling the de-trended distribution of each variable input item (items like fertilizer) and revenue item (like soybean prices), then randomly draw from each distribution to create 5,000 different combinations of input and revenue item prices. We also model variability in yield by drawing from the distribution of the relative yield results from field trials. Knowing the distribution of each item keeps the simulation within realistic values. Then, we see what profits are at different salinity levels for each of the 5,000 simulations for each seed. This provides the profit distributions for the profit confidence intervals.

Estimated Profitability Impacts of Salt-Tolerant Soybean Varieties

Results from the profit simulation analysis are succinctly depicted in Figure 2. For each soybean variety, there is an average profit estimate (the solid line) and upper/lower confidence intervals (the dotted lines around the solid line). The graph shows how profits per acre change (vertical black line on left) as the soluble salt index increases (as one moves right along the horizontal black line near the bottom). Each solid-colored line shows the expected change in profits for the salt-intolerant and different tolerant varieties. For example, the red line is the salt-intolerant variety, and it shows that expected profits are slightly above $250 per acre at a soluble salt index of zero (the leftmost edge of the line). When the soluble salt index enters the third zone (Z2), the red line passes below the horizontal black line, which means that profits for the salt-intolerant variety have gone below zero.

Figure 2. Estimated Per-Acre Profit of Different Levels of Saltwater Intrusion for Salt-Intolerant and Salt-Tolerant Soybean Varieties



Note: Authors' calculations based on simulation results. (a) Dotted lines are 95% confidence intervals. (b) Z0 is non-impacted (SSI<33), Z1 is sporadic salinity (33<SSI<53), Z2 is recurring episodic salinity (53<SSI<93), Z3 is low chronic salinity (93<SSI<173), and Z4 high chronic salinity (SSI>173).

When saltwater intrusion is at the two lowest levels - non-impacted (Z0) and sporadic salinity (Z1) - the estimated profits from planting both the salt-intolerant and salt-tolerant varieties are statistically equivalent given the overlapping confidence intervals in these zones. That is, profits are likely to be about the same. Although the salt-intolerant variety is trending downwards at a steeper rate, the overlap in the confidence intervals across varieties suggests that profits are statistically the same across the four varieties. This means that when the field experiences less than recurring episodic salinity (Z2), it might be hard to discern profit differences between the four varieties.

Our analysis suggests that farmers planting a salt-intolerant variety will experience a complete profit loss when salinity is about 100 to 125 SSI (in the lower end of Z3), while profits will more likely still be positive when a salt-tolerant variety is planted around this SSI value. This means that salt-tolerant varieties will not be helpful at high levels of saltwater intrusion (e.g., for SSI at the mid-to-higher end of Z3, and larger (Z4)), but it can help mitigate profit losses when saltwater intrusion is at the lower end of the low chronic salinity stage (Z3). Thus, the best use case scenario for salt-tolerant varieties may be when salinity exposure is generally lower – when there is recurring episodic salinity and low levels of chronic salinity. That is, a salt-tolerant variety might resist an acute but one-time salt exposure that would otherwise severely damage a non-tolerant variety, or a salt-tolerant variety will perform better when salt exposure is lighter and seasonal (perhaps from ocean spray). It is also worth noting that when considering the three salt-tolerant varieties, the profit performance of all three varieties is statistically equivalent across all levels of saltwater intrusion. The overlapping confidence intervals for the three salt-tolerant varieties mean that profits from these varieties will be about the same statistically, regardless of the degree of saltwater intrusion.

Note: Soybean growth in a salt water-impacted field in Hyde County, N.C. (center); with areas of normal growth (left photo) and damaged plants (right photo). Photo from: https://content.ces.ncsu.edu/effects-of-wind-induced-sodium-salts-on-soils-in-coastal-agricultural-fields.

Concluding Thoughts

SWISLR is becoming a major problem in coastal agricultural regions. Several short-term and long-term adaptation strategies can help row crop producers deal with SWISLR. One approach is to adopt salt-tolerant crop varieties to mitigate the adverse yield impacts of saltwater intrusion. Findings from our simulation analysis suggest that salt-tolerant varieties can be an effective means to mitigate the potential profit loss from low-to-moderate levels of saltwater intrusion. If soybean farmers in coastal areas of North Carolina expect to experience low-to-moderate levels of saltwater intrusion in the future, then investing in salt-tolerant varieties may help avoid complete profit loss when milder saltwater intrusion occurs. The additional seed cost associated with these salt-tolerant varieties is likely worth the avoided yield and profit loss in cases of low-to-moderate levels of saltwater intrusion. Nonetheless, it is important to note that the net economic benefits from using these salt-tolerant varieties only materialize when experiencing saltwater intrusion in the field. Hence, farmers need to assess their individual circumstances and determine whether the likelihood and extent of saltwater intrusion in their fields is at the low-to-moderate levels to make these salt-tolerant varieties worth the investment. While there have been research investments in breeding salt-tolerant varieties (Yamaguchi & Blumwald, 2003), and scientists are identifying the mechanisms by which certain crops like wheat (Roy & Negrao, 2014) and quinoa (Emmerich, 2017) resist salt, plant breeders have only recently been paying serious attention to the issue (Melino & Tester, 2023). While developing salt tolerance and keeping the current desirable crop characteristics may be a challenge (Shannon & Qualset, 1984), we are hopeful that growers will have a wider array of salt-tolerant crop varieties to choose from soon.

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