Cradle to farm gate lifecycle inventory and water quality impacts associated with nutrients used for corn, soy, and stover biomass feedstocks

Susan E. Powers, Ph.D., P.E.,
Center for the Environment, Clarkson University, Potsdam NY 13699-5715

The production of corn or soybeans for bio-based fuels and materials requires significant inputs of nitrogen (FN) and phosphorus fertilizer (FP) to increase grain yields. Approximately 50% of these nutrients are integrated into plant biomass. The remaining 50% is volatilized, leached into surface and groundwater, or transformed into gaseous species such as N_2, NO, or N_2O. Recent efforts to complete lifecycle inventories for bio-products based on corn, soy or corn stover feedstocks have largely ignored flows of fertilizer nitrogen and phosphorus to surface water bodies. The studies that have included nutrient leaching generally assume that a constant fraction of the fertilizer is leached, typically ~24-30%. This approach fails to integrate the very wide variability in leaching rates and, therefore, fails to adequately predict yearly variability in eutrophication and hypoxia.

Eutrophication is considered one of the most pervasive problems affecting water quality in the United States, especially in the Midwest where fertilizers are used extensively for agriculture. In the process of eutrophication, the presence of excess N and P nutrients allows over production of plant biomass in waterways. The eventual degradation of this biomass consumes oxygen resulting in hypoxic conditions (low oxygen concentrations) in the most severe cases of eutrophication. Fertilizer use on corn and soybean farms in the Midwest is considered one of the primary contributors to the growing hypoxic zone in the Gulf of Mexico. Through a combination of excessive nutrient loads and hydrodynamic conditions, a region along the coast of Louisiana that is approximately the size of the State of Massachusetts is considered ecologically dead most summers. This results in the death of species that are not sufficiently mobile and changes in biodiversity and food webs throughout the region as larger species migrate to other locations. Researchers for federal agencies have suggested that reducing the average nitrogen load by 30% will help to limit the hypoxic zone to acceptable levels. Other researchers predict that a 40-45% reduction in total nitrogen loads (TN) would be required to meet this goal.

The objective of this work is to quantify life cycle inventories and water quality impacts associated with nutrients used for feedstock generation. Mathematical models were developed to describe nitrogen and phosphorus flows and distributions between environmental compartments. Leaching of nutrients to surface water is estimated as a linear function of the rainfall to best approximate the annual variability in nutrient loads. These models were used in conjunction with nutrient use, crop area, and crop yield statistics for a 13-year period (1988-2000) for 35 counties in the eastern half of Iowa. These counties approximate the watersheds for the Iowa, Wapsipinicon and Skunk Rivers. Total nitrogen and phosphorus concentrations and loads have been measured for decades at the point where these rivers discharge to the Mississippi River. The calibration of the nutrient leaching model to these measured water quality data provided a means of reducing the uncertainty in estimating the annual variability in nutrient leaching.

The nutrient leaching model was coupled with LCA data describing emissions occurring during fertilizer manufacture and energy production and consumption, providing a cradle-to-farm gate life cycle inventory for corn, soybeans and stover. Three separate scenarios were considered:

- Scenario 1, the base case, considered corn-soybean rotations (C-S) with conventional till and no stover collection;
- Scenario 2 was C-S with no till and stover collection at a maximum rate allowable with acceptable erosion levels; and,
- Scenario 3 was the same as 2 except for continuous corn (C-C) rather than C-S.

The LCI for each of these scenarios was quantified and used to determine eutrophication potentials for each of the 13-year study period to incorporate variability with rainfall.

The TN and TP leaching models that correlate the fraction of FN and FP that leaches to annual rainfall in each county provide good representation of the measured variability in nutrient loads discharged from eastern Iowa watersheds to the Mississippi River (Figures 1 and 2). The ability to calibrate this model reduces the uncertainty in the leaching estimates for the base case scenario than would be possible without the site-specific water quality data. There are, however, more significant uncertainties associated with the allocation of the total loads between corn and soy and the predictions of loads when moving to the no till, stover collection scenarios. Two radically different approaches were used to estimate the allocation of nitrogen flows between corn and soybeans. Between the two methods, between 60 and 99% of the TN leached from the overall C-S system would be allocated to corn, with the balance allocated to soybeans. The wide range between these estimates stems from a poorly understood symbiosis of nitrogen flows within the C-S rotation. It is not apparent how to best integrate this into an LCA.

The primary focus of this research was the eutrophication potential associated with the three scenarios. TN and TP flows to the Mississippi River and Gulf of Mexico were aggregated into an overall eutrophication potential, expressed as equivalent mass of NO_3-N. To provide some perspective and determine the impact of these loads, predicted eutrophication loads were compared to the target reduction in TN flows to limit the size of the Gulf of Mexico

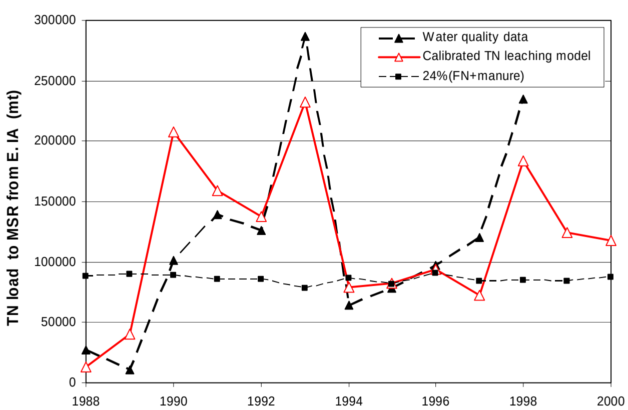

Fig. 1: Calibrated TN leaching model compared with actual measured TN loads to the Mississippi River

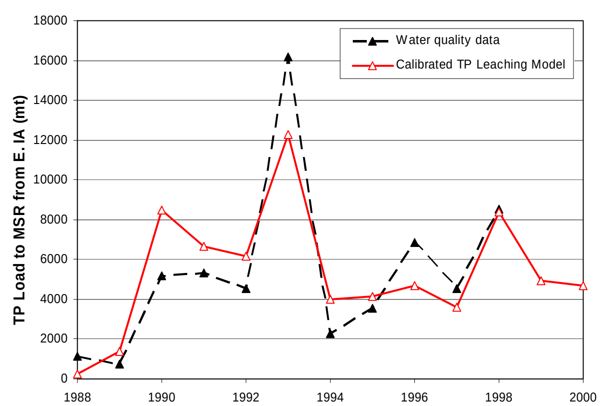

Fig. 2: Calibrated TP leaching model compared with actual measured loads to the Mississippi River

hypoxic zone and recommended water quality standards to control eutrophication at a local level.

The results of this analysis show that the eutrophication potential for the base case already exceeds acceptable limits. TN and TP discharges from C-S lands exceed the maximum loads defined by the proposed water quality standards each of the 13 years of this study. Limits established by the goal of a 30% reduction in the average TN load are also exceeded in approximately half of the years. If additional sources of nutrients discharged from the study area are considered, it is estimated that the eutrophication potential is higher than recommended except under drought conditions.

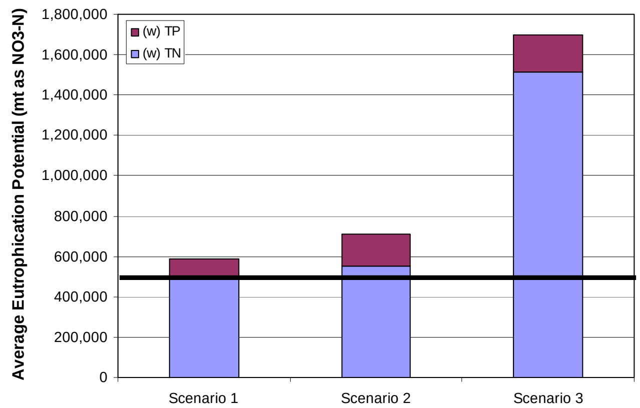

Fig. 3: Average eutrophication potential for the three scenarios (solid line represents goal for limited hypoxia; 30% reduction of '80–'96 TN average)

Changing the current conditions to harvest stover for bio-fuels or materials production increases the eutrophication potential above the base case (Figure 3). The C-S scenario (2) results in a 21% increase in the eutrophication potential, while the C-C scenario (3) almost triples the total load of TN and TP (as equivalent NO_3-N). In either case, the increase is to a system that has already exceeded its assimilative capacity for nutrients. For the C-S system, it is likely that careful management of fertilizers used at the farm could help to limit nutrient leaching. With the very high nitrogen fertilizer demand in a C-C system, however, it is not likely that management practices could sufficiently overcome the detrimental effects of eutrophication resulting from the high leaching rates.

The generation of this life-cycle data was required to provide a more comprehensive understanding of the environmental impacts associated with increased use of biomass for fuels and other products. The LCA quantifies impacts on very different components of the environment, but does not judge which of these components are more important. The LCA results are necessary, but not sufficient to allow decisions regarding future energy sources to be made. In the United States, the goal of current policies is to reduce our dependence on imported energy. The LCA results can be used to quantify the environmental benefits and detriments associated with this goal and can help identify key concerns that should be addressed as we move forward with this goal (e.g., improved nutrient management to reduce water quality degradation). At some point, a balance needs to be defined between the various goals of different interest groups in a manner that then overall environmental impact from biomass fuels and products is considered acceptable, leading to a sustainable materials and energy source for the future.