NON-DETERMINISTIC SIMULATIONS TO EVALUATE THE IMPACT OF UNCERTAIN MODEL INPUTS ON PREDICTIONS OF STREAMBANK RETREAT AND SEDIMENT TRANSPORT RATES ACROSS THE NORTH CAROLINA PIEDMONT REGION

by

Elizabeth Beyer

Advised by Celso Castro-Bolinaga, Ph.D.

A Technical Paper

Submitted to

The K.K. Barnes Student Paper Award Competition

American Society of Agricultural and Biological Engineers (ASABE)

Student Signature: Elizabeth Beyer Date: May 14, 2021

Department Head Signature: Date: May 14, 2021

\footnote{ASABE membership number: 1059060; email address: egbeyer@ncsu.edu; telephone number: (919) 886-2445; institution name: North Carolina State University; institution location: Raleigh, North Carolina; graduation date: anticipated May 2022.}
This research is an extension of the author’s initial role as a research assistant for the laboratory of Celso Castro-Bolinaga, Ph.D. The author aided in the collection of field and laboratory data outlined in this study. This process of data collection opened the door to a previously untapped resource of stream data in the Piedmont physiographic region of North Carolina, USA. The author undertook a yearlong independent research project, advised by Dr. Castro-Bolinaga, that sought to evaluate the performance of a model to predict streambank retreat and sediment transport rates in the region using the collected data.

This study is a form of experimental work in which the author contributed to the work. Alexis Swanson managed the collection of the initial data and development of the linear model for critical shear stress. Jonathan Lewis developed the geometry of the model used in the non-deterministic simulations. The author aided the collection of the data from the field and the testing of the data in the laboratory, analyzed the data for use in the simulations, conducted the simulations, and performed the subsequent uncertainty quantification analysis.
Abstract

The development of the built environment has drastically changed the magnitude and frequency of water and sediment fluxes to streams. If pronounced, such changes can result in excessive channel-bed aggradation and degradation as well as streambank retreat, thereby impacting the geomorphic integrity of streams and altering their capacity to support biodiversity and perform ecological functions. Numerical models are used by interest groups to evaluate these hydro-morphodynamic phenomena, helping them to understand how streams respond to external drivers such as climate and anthropogenic alterations. Nonetheless, results and predictions from these modeling efforts are constrained by the uncertainty associated with the characterization of model inputs. The objective of this research was to perform uncertainty quantification analyses for quantifying how the variability of key inputs affects modeling predictions of streambank retreat and sediment transport rates. Specifically, non-deterministic simulations were performed using the one-dimensional (1-D) Hydrologic Engineering Center - River Analysis System (HEC-RAS) hydro-morphodynamic model with the Bank Stability and Toe Erosion Model (BSTEM) to propagate the uncertainty associated with channel-bed and streambank material gradation, water discharge, bank sediment qualities (i.e., temperature, electrical conductivity, and moisture content), and streambank erodibility parameters through the system. The type of uncertainty (i.e., aleatory or epistemic) and the range of variability for each input were determined from field data collected across thirteen streams in the North Carolina Piedmont Region (NCPR) and United States Geological Survey (USGS) gage stations located in the surrounding area. Forty-five preliminary simulations were conducted using sample inputs corresponding to the ranges of variability determined from the NCPR. The initial results of the simulations indicate that extreme flow events yield higher levels of uncertainty propagated by the model.

Introduction

According to the United States Environmental Protection Agency (EPA), one of the leading causes of stream impairment in the United States (US) is excess sediment (USEPA, 2017). Sediment,
which often carries chemical pollutants like phosphorus adsorbed to its particles, can accumulate in downstream bodies of water that serve as drinking water supplies or flood control reservoirs (Schleiss et al., 2016). Streams which transport excess sediment might be subject to poor water quality and the degradation of aquatic ecosystems (Owens et al., 2005; Wood & Armitage, 1997). In some cases, the sediment which impairs streams and watersheds comes from the channel and banks of the streams themselves (Fox et al, 2017). Although stream channels and banks may change through the natural processes of channel-bed aggradation and degradation as well as streambank retreat, excessive changes can make streams unstable, which can exacerbate flooding and further erosion of sediment (Doyle & Harbor, 2003; Lewin & Brewer, 2001; Simon & Thomas, 2002).

There are a number of potential causes to the problem of excessive sediment pollution. Land use transformation on the watershed scale has increased the degree of impervious surfaces, leading to an accumulation of runoff or stormwater during a precipitation event (O’Driscoll et al., 2010). Higher flow velocities and water discharges can erode more and larger grained sediment particles. As regions urbanize, channels are often reconfigured or managed to fit the needs of the surrounding population, sometimes in manners that tend to exacerbate the impact of flows. Floodplain area may be reduced as buildings encroach upon streams, smoother-surfaced culverts may be used to pass streams beneath roadways, and meandering streams may be straightened to reduce overall stream area. Increasing non-stationarity in regional climate can escalate the issue as storm events become unpredictable or even intensified (Syvitski, 2003).

Stream restoration is an applied science that seeks to improve water quality and aquatic habitats in streams that have been affected by these anthropogenic and climatic alterations (Wohl et al, 2015). Restoration projects may take the form of modifications to the stream channel planform, cross-sectional geometry, and longitudinal profile (Wohl et al, 2015). In-stream structures and streambank stabilization practices, such as riprap, are frequently used to maintain restoration projects (Bigham, 2020). In general, these stream modifications may be the same ones which have led to the exacerbated conditions in the first place. What differentiates stream restoration from other modes of stream manipulation is the definition of
restoration: to assist the improvement of hydrologic, geomorphic, and ecological processes and replace lost or degraded elements of the natural system (Wohl et al., 2015).

It can be very difficult to predict streambank retreat and sediment transport rates for restoration purposes due to the spatiotemporal variability of stream characteristics and applied forces (Rosburg & Nelson, 2017). As interest in stream restoration continues to grow, there is an increased need to strengthen the scientific understanding of stream responses to variable conditions. Various models have been developed to predict streambank retreat and sediment transport rates so that stream restoration projects can be optimized (Klavon et al., 2017). One such model is the one-dimensional (1-D) Hydrologic Engineering Center - River Analysis System (HEC-RAS) hydro-morphodynamic model, which can be paired with with the Bank Stability and Toe Erosion Model (BSTEM) to evaluate streambank retreat and sediment transport rates. However, there is uncertainty associated with model inputs that can ultimately affect the numerical results.

The objective of this study was to assess the uncertainty of streambank retreat and sediment transport rates as predicted by 1-D HEC-RAS with BSTEM when subjected to variable conditions of channel-bed and streambank material gradation, water discharge, and streambank erodibility parameters characteristic of the NCPR. Non-deterministic simulations were conducted to evaluate how the variability of hydro-geomorphic conditions affected the prediction of the streambank retreat and sediment transport rates by the model. To assess the uncertainty propagated by the model, cumulative distribution functions of the system response quantities from the simulations were compared. Ultimately, this study aimed to offer guidance on the combination of physical characteristics most critical to evaluating and predicting streambank retreat and sediment transport rates for stream restoration projects in the NCPR and physiographically similar regions.

**Methods**

**2.1 Study Area**
The study area consisted of thirteen streams in the Piedmont physiographic region of North Carolina, USA (hereafter referred to as NCPR). Located between the coastal and mountainous regions of the state, the NCPR is home to a growing number of streams designated as “impaired” by the North Carolina Department of Environmental Quality (NCDEQ, 2020) such that there is a high need for stream restoration projects. The NCPR is also unique in its high degree of geomorphic variability, which makes it difficult to establish post-restoration standards that can be widely used. Together, these factors determine that there is a high demand and need for an analysis of model uncertainty in the NCPR. The thirteen streams and their respective field sites were chosen based on watershed and channel properties to accurately represent the variable physiographic characteristics of the entire NCPR.

One stream from the series, Richland Creek, yielded the fixed geometric characteristics for the simulations. Richland Creek is a second-order, sand-bed stream within the Neuse River basin (USGS Hydrologic Unit 03020201). It drains an area of 20.2 square kilometers characterized by thirty-five percent forest land, thirty-five percent agricultural land, and thirty percent developed land, with less than ten percent impervious area (USGS, 2021). For all thirteen streams, channel-bed and streambank material gradation, water discharge, bank sediment qualities (i.e., temperature, electrical conductivity, and moisture content), and streambank erodibility parameters were characterized. The characteristics of each stream and its respective drainage area are available supplementally.

2.2. Simulated Reach Geometry

Kassa (2019) studied a 905 meter long reach of Richland Creek that extended from Stadium Drive at its upstream end (35°59'5.1"N, 78°31'10.93"W) to Durham Road at its downstream end (35°58'41.9"N, 78°31'25.6"W) in the Town of Wake Forest in Wake County, North Carolina. The average slope along the study reach was measured as 0.0026 meters per meter, with an average channel width of 8.4 meters and an average bankfull depth of 1.07 meters. For performing the non-deterministic numerical simulations, a simplified channel geometry was generated using ten identical trapezoidal cross-sections aligned 100 meters apart. The cross-sections are 8.4 meters in width, 1.07 meters in depth, and vary in
elevation according to the measured average slope of 0.0026 meters per meter. The horizontal component of each bank is 1.2 meters long, which yields a bank slope of approximately 1.1 meters per meter. These specifications for stream geometry were used in 1-D HEC-RAS with BSTEM with default values for all other geometric inputs, except for the Manning’s n value, which was set to 0.04 due to the characteristics of the physical reach (Arcement & Schneider, 1989).

2.3 Physical Characteristics of Streams Across the NCPR

At each stream site, two cross sections were chosen for data collection based on erosional evidence. The soil temperature, electrical conductivity, and soil moisture content of the bank material were measured and recorded for each cross section. A jet erosion test (JET) (e.g., Daly et al., 2013) was performed in situ to measure the critical shear stress and the erodibility coefficient of the bank material (which are collectively known as erodibility parameters). Soil cores were collected adjacent to each JET for subsequent laboratory analysis of bank material properties. If there were visible horizons in the bank of the cross section, this procedure was repeated for each horizon. Sediment samples were also collected from the bed of each stream cross section.

The soil cores and the sediment collected from the stream bed were tested following the standards of the American Society for Testing and Materials (ASTM) to obtain information about the median grain size, the coefficient of uniformity, the coefficient of curvature, the geometric standard deviation, the silt and clay content, and the overall grain size distribution. A preliminary multiple linear regression model based on the collected parameters was developed to predict the critical shear stress, $\tau_c$ (in Pascals):

$$\log(\tau_c) = -5.78 + 0.002Temp - 1.90EC - 1.77MC - 1.29\log(D_{50}) + Cu + Cc - 0.13GSD - 0.009Pass2$$

(1)

where $Temp$ is the soil temperature (in degrees Celsius), $EC$ is the electrical conductivity (in Siemens per meter), $MC$ is the moisture content (as a percentage), $D_{50}$ is the median grain size (in meters), $Cu$ is the coefficient of uniformity, $Cc$ is the coefficient of curvature, $GSD$ is the geometric standard deviation of
the grain size sample, and Pass200 is the percent passing the number two hundred sieve, that is, the silt and clay content.

Mean daily water discharge was determined based on data from USGS gage stations located along the thirteen streams. To mimic the flow levels experienced by the stream cross sections studied, gage data were used when the gage was located at a point which drained an area greater than five square kilometers and less than twenty-five square kilometers.

2.4 Model Descriptions

HEC-RAS is a model that performs hydraulic, sediment transport, and bed change computations in rivers and channels (Brunner, 2016). It is process-based, meaning that it makes predictions by numerically solving the physics-based equations which govern the movement of water and sediment. It functions on the reach scale and can therefore account for the cumulative effect of multiple channel cross-sections. BSTEM is a model that simulates streambank retreat due to geotechnical failure and fluvial erosion (Klavon et al., 2017; USDA-ARS, 2016). It is also process-based, but unlike HEC-RAS, BSTEM functions on a local scale, in that it evaluates a single channel cross-section at a time. 1-D HEC-RAS can be coupled with BSTEM to allow for both the computation of vertical changes of the channel bed and lateral changes due to streambank retreat.

2.5 Uncertainty Quantification Analysis

2.5.1 Uncertainty Classification

The uncertainty of model inputs was classified as aleatory or epistemic to determine the variables’ treatment for subsequent non-deterministic simulations. Aleatory uncertainty—which is also called irreducible uncertainty, stochastic uncertainty, or variability—is uncertainty due to inherent variation. This type of uncertainty can be characterized through a probability density distribution, such as a probability density function or a cumulative distribution function (CDF). Epistemic uncertainty—which is also called reducible uncertainty or ignorance uncertainty—is uncertainty due to a lack of knowledge. If
sufficient knowledge is added, epistemic uncertainty can theoretically be eliminated. Knowledge may be added through many means, including an accumulation of experimental data, a reduction of computer round-off error, and an improvement of numerical approximation. For the purpose of this study’s simulations, the stream geometry is left fixed and can therefore be treated as deterministic (Roy & Oberkampf, 2011). The uncertainty classification of the other model inputs is shown in table 1.

Table 1. Uncertainty classification of model inputs, except stream geometry, which is treated as deterministic.

<table>
<thead>
<tr>
<th>Model Input</th>
<th>Uncertainty Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed sediment gradation</td>
<td>Epistemic</td>
</tr>
<tr>
<td>Bank soil temperature</td>
<td>Epistemic</td>
</tr>
<tr>
<td>Bank sediment electrical conductivity</td>
<td>Epistemic</td>
</tr>
<tr>
<td>Bank sediment moisture content</td>
<td>Epistemic</td>
</tr>
<tr>
<td>Bank sediment gradation</td>
<td>Epistemic</td>
</tr>
<tr>
<td>Flow</td>
<td>Aleatory</td>
</tr>
</tbody>
</table>

2.5.2 Non-Deterministic Simulations

The model inputs characterized by epistemic uncertainty were sampled randomly for each simulation. First, the grain size distributions for the sediment collected from the beds at each sampled cross section were plotted together in figure 1.
Figure 1. Grain size distributions for bed sediments shown with sampling parameters $dx_1$ and $dx_2$.

Each bed material sample was characterized by its median grain size. A random sample was taken from the range of median grain sizes. To preserve the general S-shape of a grain size distribution curve, $dx_1$ was calculated as the difference between the sample median grain size and the smallest median grain size, and $dx_2$ was calculated as the difference between the sample median grain size and the largest median grain size. Both $dx_1$ and $dx_2$ were normalized by the range of median grain sizes. Samples for the grain size of the sediment at zero percent finer, twenty percent finer, forty percent finer, sixty percent finer, eighty percent finer, and one-hundred percent finer were then calculated using the ratio between $dx_1$, $dx_2$, and the range of the respective grain sizes from the grain size distributions of the bed material. For example, the grain size of the sediment at twenty percent finer was linearly approximated for each bed material sample. The smallest grain size of this series, plus $dx_1$ times the range of these grain sizes, yielded a sample grain size at twenty percent finer. The final bed material grain size distribution curve for a simulation had six points with grain sizes for zero percent finer, forty percent finer, fifty percent finer, sixty percent finer,
eighty percent finer, and one-hundred percent finer. Linear approximations were made between these points to find the percent finer values for the grain sizes specified by 1-D HEC-RAS with BSTEM. A sample median grain size was also taken from the range of median grain sizes for the bank material. The previously detailed method was used to create random bank grain size distributions for the model.

The following section describes the method used to determine the erodibility parameters required for a simulation using 1-D HEC-RAS with BSTEM. For each random bank grain size distribution, the coefficient of uniformity ($Cu$) was calculated given the following relationship:

$$Cu = D60 \div D10 \ (2)$$

where $D60$ is the grain size (in millimeters) of the sample bank material such that sixty percent of the material is finer by weight, and $D10$ is the grain size (in millimeters) of the sample bank material such that ten percent of the material is finer by weight. The coefficient of curvature ($Cc$) was calculated given the following relationship:

$$Cc = (D30)^2 \div (D60 \times D10) \ (3)$$

where $D30$ is the grain size (in millimeters) of the sample bank material such that thirty percent of the material is finer by weight, and $D60$ and $D10$ are the variables described previously. The geometric standard deviation ($GSD$) was calculated for the points in the final bank material grain size distribution curve. The percent clay and silt content ($Pass200$) was calculated using a linear approximation of this curve, given a grain size of 0.074 millimeters. The median grain size ($D50$, in millimeters) was sampled previously.

A random sample was taken from the range of data for soil temperature ($Temp$, in degrees Celsius), electrical conductivity ($EC$, in Siemens per meter), and moisture content ($MC$, as a percentage). For a simulation, these values were inputted into equation 1 to calculate the critical shear stress ($\tau_c$, in Pascals). The erodibility coefficient $k_d$ (in cubic meters per Newton-seconds) was then calculated using the following relationship from BSTEM (Clark & Wynn, 2007; USDA-ARS, 2016):

$$k_d = 0.2 \tau_c^{-0.5} \ (4)$$
Friction angle, cohesion, saturated unit weight, and unsaturated shear strength angle (shown in table 2) were set to the default BSTEM values for angular sand, as all tests of bank material determined material which could be classified as sand.

Table 2. Default values of additional BSTEM parameters for angular sand classification.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle</td>
<td>32.3 degrees</td>
</tr>
<tr>
<td>Cohesion</td>
<td>0.4 kiloPascals</td>
</tr>
<tr>
<td>Saturated unit weight</td>
<td>1.8858 kilograms per cubic meter</td>
</tr>
<tr>
<td>Unsaturated shear strength angle</td>
<td>15 degrees</td>
</tr>
</tbody>
</table>

According to Roy and Oberkampf (2011), when there are sources of both aleatory and epistemic uncertainty in a model, the propagation of each type of uncertainty must be separated. For each sample of all the epistemic uncertainties, the aleatory uncertainties should be propagated through the model to produce a CDF of the desired system response quantities. In this study, a flow duration curve was created for the mean daily discharge data collected from the appropriate gages. For every sample of the epistemic uncertainties, the probability of exceedance was sampled fifteen times. Each probability of exceedance yielded a discharge sample via the flow duration curve. Non-deterministic simulations were conducted using 1-D HEC-RAS with BSTEM with the combination of the variables characterized by epistemic uncertainty and each sample of the discharge, the variable characterized by aleatory uncertainty. Each round of non-deterministic simulations yielded values of streambank retreat and sediment transport rates, which were used to create a CDF. In total, three rounds were conducted, yielding three CDFs from forty-five simulations. The widest extent of the collection of CDFs was used to form a probability box, or p-box, to reflect the uncertainty of the system response quantities given the uncertainty of the model inputs. This uncertainty propagation method is shown in figure 2.
The bed material gradation was entered into 1-D HEC-RAS with BSTEM. One discharge sample at a time was used as the quasi-unsteady flow for sediment analysis. The downstream boundary condition was set to “Normal Depth,” with a friction slope of 0.0126 and the upstream boundary condition was set to “Flow Series.” The discharge sample was only inputted at cross-section 10, which preserved a constant flow over the reach. The water temperature was set to twenty-five degrees Celsius for the duration of the simulation. From Kassa (2019), the transport function was Yang. Copeland was chosen as the sorting method as it was developed for sandy beds, and Ruby was selected for the fall velocity method. The maximum bed erosion depth was set to one meter for every cross-section. Sediment analysis was conducted using the fixed channel geometry and simulated quasi-unsteady flow and sediment data for a thirty day period. The cumulative mass change of the bed (in tonnes), which yields a sediment transport rate (in tonnes per day) over a twenty-four hour period, was evaluated. The final twenty-four hours of the simulation were chosen to allow sufficient time for the model to stabilize, and the data was taken from cross section five since it represents a mid-reach point in the channel.
Results and Discussion

The model inputs previously characterized by aleatory or epistemic uncertainty were evaluated to have the ranges shown in table 3.

Table 3. Uncertain model inputs and their measured ranges across the NCPR.

<table>
<thead>
<tr>
<th>Model Input</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed sediment gradation</td>
<td>Varies; range of median grain sizes is 0.36 to 2.09 mm</td>
</tr>
<tr>
<td>Bank soil temperature</td>
<td>4.6 to 31.7°C</td>
</tr>
<tr>
<td>Bank sediment electrical conductivity</td>
<td>0.02 to 0.53 S/m</td>
</tr>
<tr>
<td>Bank sediment moisture content</td>
<td>5 to 55%</td>
</tr>
<tr>
<td>Bank sediment gradation</td>
<td>Varies; range of median grain sizes is 0.06 to 1.38 mm</td>
</tr>
<tr>
<td>Flow</td>
<td>0.23 to 138 cfs</td>
</tr>
</tbody>
</table>

The bed gradation samples used in the non-deterministic simulations are shown in figure 3.
Figure 3. Bed gradation samples used in non-deterministic simulations.

The discharge samples used in the non-deterministic simulations are shown in figure 4.
Figure 4. Discharge samples and corresponding exceedance probabilities used in non-deterministic simulations. Note that some points are superimposed due to repetition in the sampling method, causing there to be visually fewer than fifteen distinct points.

Finally, the CDFs developed from the non-deterministic simulations are shown in figure 5.

Figure 5. The CDFs developed from non-deterministic simulations.
A CDF shows the probability that the actual sediment transport rate is less than or equal to a corresponding sediment transport rate. Negative sediment transport rates indicate bed erosion (or channel bed degradation) while positive sediment transport rates indicate bed deposition (or channel bed aggradation). When the CDFs are plotted together, there is a range of interval-valued probability between the lower CDF and the higher CDF, and for every probability, there is a range of interval-valued response between the lagging CDF and the leading CDF. These ranges define the model’s $p$-box and are particularly pronounced at both ends of the ranges of possible sediment transport rates and probabilities. For example, a probability around 0.9 corresponds to a much larger range of potential sediment transport rates than a probability of 0.4 does.

In general, larger flow levels corresponded with larger magnitudes of sediment transport rates, so the width of the $p$-box, or the level of uncertainty of the sediment transport rate, at the tails of the CDFs can be attributed to extreme flow events in the NCPR. The simulations yielded slightly more positive values of sediment transport rate, that is, there were more instances of bed deposition than erosion. Future simulations might detect a pattern of bed deposition rather than erosion across the NCPR.

Due to project constraints, BSTEM was not incorporated into the final simulations, and therefore the system response quantities related to streambank retreat were not evaluated. However, any changes of the streambank, such as channel widening, would theoretically have a direct impact on the simulated bed material, and therefore can be assumed to be included in the system response quantity of bed sediment transport rate. Future work is recommended to directly include the BSTEM parameters (that is, the bank erodibility parameters) and conduct further non-deterministic simulations for uncertainty quantification analysis of streambank retreat system response quantities, namely, eroded bank area and failure volume.

Conclusions

An uncertainty quantification analysis was conducted to examine the uncertainty of streambank retreat and sediment transport rates propagated by a model from the uncertainty of its inputs, with the
objective of critically assessing the combination of physical characteristics most critical to evaluating and predicting these system response quantities. Specifically, channel-bed and streambank material gradation, water discharge, and streambank erodibility parameters collected from the Piedmont physiographic region of North Carolina, USA was sampled for analysis via 1-D HEC-RAS with BSTEM. Non-deterministic simulations were conducted to evaluate how the variability of hydro-geomorphic conditions characteristic of the NCPR affected the prediction of streambank retreat and sediment transport rates. Cumulative distribution functions of the system response quantities from the simulations were compared to identify the resulting intervals of uncertainty.

A probability box developed from the cumulative distribution functions showed pronounced ranges of interval-valued probability and interval-valued response at both ends of the ranges of possible sediment transport rates and probabilities. As larger, and less likely, flow levels generally corresponded with larger magnitudes of sediment transport rates, it can be assumed that uncertainty associated with extreme flow events propagated most drastically through the model. Stream restoration projects in the NCPR that make use of 1-D HEC-RAS with BSTEM, especially those that are constrained by an extreme precipitation event such as a one-hundred-year flood, should account for the uncertainty propagated by the model for these events.

Simulations indicated slightly more instances of bed deposition rather than erosion. Future work is recommended to evaluate further simulations, which might clarify this pattern for the NCPR. In general, further simulations are recommended to better understand the patterns of uncertainty propagated by the model in this study. By incorporating BSTEM, uncertainties may be propagated through the model for measurements of streambank retreat.

Acknowledgements

The author would like to thank Celso Castro-Bolinaga, Ph.D. for advising this study, Alexis Swanson for her management of the data collection process and her mentorship, and Jonathan Lewis for his contribution to the development of the model. In addition, the author would like to thank Lucie
Guertault, Ph.D. for supporting the project and providing mentorship to the author. Finally, the author would like to acknowledge the support of North Carolina State University’s Department of Biological and Agricultural Engineering and the Department Head, Garey Fox, Ph.D.

References


https://doi.org/10.13031/trans.13647


https://doi.org/10.13031/2013.22415

https://doi.org/10.13031/trans.56.10350

https://doi.org/10.1002/esp.516


https://doi.org/10.1007/s00267-016-0671-9


https://doi.org/10.1016/S0169-555X(01)00061-7


https://doi.org/10.3390/w2030605


https://doi.org/10.1111/1752-1688.12511


