Journal of Great Lakes Research 42 (2016) 637–648

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Identifying the origin of waterbird carcasses in Lake Michigan using a neural network source tracking model

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ARTICLE INFO

Article history:
Received 7 September 2015
Accepted 10 February 2016
Available online 19 March 2016

Communicated by Craig Hebert

Index words:
Avian botulism
Carcass drift
Common loon
Lake Michigan
Neural network model
Waterbird

ABSTRACT

Avian botulism type E is responsible for extensive waterbird mortality on the Great Lakes, yet the actual site of toxin exposure remains unclear. Beached carcasses are often used to describe the spatial aspects of botulism mortality outbreaks, but lack specificity of offshore toxin source locations. We detail methodology for developing a neural network model used for predicting waterbird carcass motions in response to wind, wave, and current forcing, in lieu of a complex analytical relationship. This empirically trained model uses current velocity, wind velocity, significant wave height, and wave peak period in Lake Michigan simulated by the Great Lakes Coastal Forecasting System. A detailed procedure is further developed to use the model for back-tracing waterbird carcasses found on beaches in various parts of Lake Michigan, which was validated using drift data for radiomarked common loon (*Gavia immer*) carcasses deployed at a variety of locations in northern Lake Michigan during September and October of 2013. The back-tracing model was further used on 22 non-radiomarked common loon carcasses found along the shoreline of northern Lake Michigan in October and November of 2012. The model-estimated origins of those cases pointed to some common source locations offshore that coincide with concentrations of common loons observed during aerial surveys. The neural network source tracking model provides a promising approach for identifying locations of botulinum neurotoxin type E intoxication and, in turn, contributes to developing an understanding of the dynamics of toxin production and possible trophic transfer pathways.

Introduction

Extensive mortalities of a variety of fish and waterbirds attributed to type E botulism outbreaks have been documented over the past half-century in the Great Lakes (Fay, 1966; Brand et al., 1988; Riley et al., 2008; Lafrancois et al., 2011; Chipault et al., 2015). Ingestion of the botulinum neurotoxin (BoNT) produced by the bacterium *Clostridium botulinum* often leads to paralysis and death in birds; botulinum neurotoxin type E (BoNT/E) is generally responsible for die-offs among a variety of Great Lakes waterbird species (Rocke and Friend, 1999; Chipault et al., 2015). While periodic outbreaks of type E botulism have been documented since first detected in smoked fish from Lake Superior in 1960 (Bott et al., 1966), outbreaks have become more common and widespread since the early 2000s in Lakes Michigan through Ontario (Lafrancois et al., 2011; Pérez-Fuentetaja et al., 2011; Shutt et al., 2014; Chipault et al., 2015). Type E avian botulism outbreaks across North America have been confined to the Great Lakes region (Rocke and Friend, 1999), but have resulted in more than 100,000 waterbird mortalities (Chipault et al., 2015).

Viable *C. botulinum* spores appear to be ubiquitous, including their distribution in the Great Lakes system (Rocke and Friend, 1999; Lafrancois et al., 2011); and under suitable conditions, vegetative growth occurs and BoNT/E is synthesized (Brand et al., 1988). Lafrancois et al. (2011) summarized information on environmental factors believed to contribute to *C. botulinum* spore germination and BoNT production, including appropriate temperature range, anaerobic conditions, and presence of decaying organic matter. Historic avian type E botulism outbreaks on Lake Michigan have tended to occur in association with years of low water levels and warmer surface water temperatures (Lafrancois et al., 2011). Scientists have speculated on mobilization of BoNT/E through the food chain, including the role played by invasive species (e.g., dreissenid mussels and round goby, *Neogobius melanostomus*), but sites of BoNT/E production and transfer through food-chain linkages have not been confirmed (Getchell and Bowser, 2006; Lafrancois et al., 2011).

Monitoring the appearance of waterbird carcasses on beaches provides the primary means of assessing spatial and temporal patterns, as well as magnitude, of die-offs resulting from type E avian botulism on the Great Lakes (Chipault et al., 2015). Interpreting the actual site of bird exposure to prey containing BoNT/E from beach surveys is hampered from a lack of information on the drift patterns of carcasses, along with the confounding influences of surface currents, wind,

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http://dx.doi.org/10.1016/j.jglr.2016.02.014
0380-1330/Published by Elsevier B.V. on behalf of International Association for Great Lakes Research.

waves, and water temperature. In order to investigate the dynamics of BoNT/E production and mobilization through Great Lakes food chains, specific sites where waterbirds acquire prey containing BoNT/E need to be identified.

While drift studies have been conducted to estimate the number of seabird carcasses that wash ashore in association with oil spills (e.g., Wiese and Jones 2001), we are not aware of efforts to model the dynamics of carcass drift. The existing physical models proposed for ocean search-and-rescue (Su et al., 1997; Anderson et al., 1998; Ni et al., 2010; Breivik et al., 2011) are based on formulation of wind and current forces on a drifting item (drifter), assuming that these two forces happen to attain a state of equilibrium and hence the drifter would have a constant velocity. These physical models, although applicable to large drifters such as boats and stalled ships, have not been extensively tested when applied to smaller drifters such as waterbird carcasses. In the Great Lakes area, numerical ocean models have been applied to trace the trajectory of small particles over a long period of time. For example, Beletsky et al. (2007) supplemented the ocean circulation model with a 3D particle transport component to trace the movement of yellow perch larvae in Lake Michigan from June to August of selected years. The size of the traced particles, in their work, ranged from 6 mm (at hatching) to approximately 50 mm (when settling happens). Particles were traced using a Lagrangian point of view, in which current velocity was simply adopted as the particle velocity. In a similar work, the dispersal process of yellow perch larvae was simulated in Lake Erie using the Princeton Ocean Model system appended with a Lagrangian particle backtracking model (Fraker et al., 2015). The authors assumed the fish larvae to be passive, neutrally-buoyant, and can move in three dimensions. In contrast, the common loons studied in the present work had a length between 400 and 600 mm and a thickness from 90 to 150 mm. In the entire drift history, a large part of the body could be above the water surface (with an initial height of approximately 42 ± 9% of the total body thickness out of water as observed from field tests), which makes the dynamics significantly different from that of fish larvae. A quick test showing the infeasibility of a current-based transport model is presented in the Methods section.

Because the bird carcass tends to drift near the water surface, wind and surface wave forcing are believed to play an important role. This view was confirmed by model sensitivity tests as presented in the Methods section. Grotmaack (2003) reviewed a number of existing physical models for describing the dynamics of small floating rigid bodies. A widely used model is expressed as

$$m(1+C_m)\frac{dV_x}{dt} = -m\left(g+\frac{\partial^2\eta}{\partial t^2}\right)\frac{\eta'}{1+\eta'^2}+\rho C_d A|V_x-V_{wx}|(V_x-V_{wx})$$

for motion in the x-direction (i.e., the wave propagation direction), where m denotes the mass of the floating body, C_m denotes its added mass coefficient, V_x and V_{wx} are the x-components of the body and the surface water velocity, respectively, g is the gravitational acceleration, η is the water surface elevation, ρ is water density, C_d denotes the drag coefficient of the body, and A denotes the characteristic area of the body relevant to its drag calculation. This equation takes both wave and current effects into account, and for the present study wind forcing could be added to the right hand side of the equation.

In real situations, however, even if a physical model could be parameterized for the added mass coefficient and the drag coefficient, the estimation of the local wave profile in a random wave environment is still challenging. Faced with various types of difficulties, we were inclined to employ an empirical model in lieu of an analytical formulation. In this approach, the only known factors are the wind, current, and wave forcing. The net effect of those determines the velocity of the floating body. The causal relationship between the forcing and the body motion is established empirically based on the data available. It is known, for example, that neural network models are effective for complex relationship and pattern recognition.

Our objective was to develop a neural network source tracking model to estimate the origin of waterbird carcasses, associated with type E botulism mortality in Lake Michigan, that were deposited at a given beach location. In turn, this information could be used to inform site-specific efforts to assess the degree to which physical and ecological factors contribute to the occurrence of BoNT/E in aquatic food webs. We based the model on empirical drift data collected for radiomarked common loon carcasses, and demonstrate the utility of the approach by comparing estimated source trajectories to common loon distribution and abundance determined through aerial surveys, to identify locations where waterbirds were likely exposed to prey containing the BoNT/E toxin.

Methods

Development of a neural network model

Neural network models, like all other types of statistical models, are used to discover inherent relationships between the dependent and independent variables. The major strength of neural network models is the representation of complexity, including nonlinearity and complex data structures. In the present work, we used three-layer, feed-forward neural network models consisting of an input layer, a hidden second layer, and an output layer. The numbers of neurons in the input and the output layers were determined by the independent and dependent variables, respectively, in the data set. The number of neurons in the hidden layer was subjected to optimization.

Current and wind velocity vectors and wave forces were included as the input variables. Current and wind velocity vectors were nonlinearly related to the forces on the drifting carcasses. As for wave forces, since a general wave spectrum (such as the Joint North Sea Wave Project [JONSWAP] spectrum) can be represented by significant wave height, peak wave period, and wave direction, we therefore determined that these three variables should be used to represent wave forces on the body. Furthermore, we represent all vectors relative to the wave direction, α_w, so that their u- and v-components are in the same direction as and perpendicular to the wave direction, respectively. As a result, six input variables were selected: wind velocity components (u_a, v_a), current velocity components (u_c, v_c), significant wave height (H_s) and peak wave period (T_p). The input layer of the neural network model, hence, has six neurons.

The response of the model for our case was the waterbird carcass velocity components, denoted as u_{BC} and v_{BC}. These components are with respect to the global coordinate system. The output layer of the neural network model hence has two neurons. The hidden layer uses a tan-sigmoid transfer function, which is defined as $\text{tansig}(x) = \frac{2}{1+e^{-2x}} - 1$, a nonlinear function with a value ranging from −1 to 1. The output layer has a pure-linear transfer function. For the hidden layer, preliminary experiments showed that 16 neurons would yield the best performance measured by the model sum-square-error (Mathworks, 2011). The architecture of the neural network model is illustrated in Fig. 1.

Once the model architecture is established, the model is trained to determine the weights and biases assigned to each (or each pair of) neurons. The Bayesian regularization back-propagation algorithm was adopted for training. This algorithm can help make the best of the data available, especially when the sample size is limited, and avoid over-fitting as well (Mathworks, 2011).

Documenting carcass drift

We attached 30-g satellite transmitters (Model Solar Argos/GPS PTT-100 Microwave Telemetry, Inc.) to common loon carcasses (collected dead on breeding grounds as a result of various causes of death) using