Simulating Sea Surfaces for Modeling Viking Age Seafaring in the Baltic Sea

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Abstract

Inferences in nautical and maritime archaeology about sailing routes in the Viking Age in Northern Europe are based today almost entirely on historical information coupled with results gained from experimental archaeology. The authors propose here a third method, which combines computer simulation with the aforementioned information sources. These sources are used together with digital bathymetric models (DBM's) of the Baltic seafloor, wind, current, and other real sailing parameters to create cost surfaces for modeling early medieval seafaring. Real sailing data obtained in the summer of 2004 with the Viking Age replica, *Ottar*, are used to model sea routes in the Baltic Sea. Both GIS-Esri and GRASS GIS are compared as modeling tools and used in least-cost path and anisotropic spread analyses to simulate sea routing in prehistoric land- and seascapes across which humans traveled more than a thousand years ago. The results of the study are evaluated in the context of experimental archaeology and modern sailing conditions in the Baltic Sea.

1 Introduction

Maritime archaeology and, especially, historical research dealing with Viking Age seafaring, have tried for a long time to decipher the reasons behind the choice of a specific sea itinerary connecting medieval trading centers in the Baltic realm. The problem is complex because explicit itineraries from that period do not actually exist and the literates who have laid them on the parchment for the posterity used their epoch's writing style and conventions. This is the case, for example, with the early 13th century King Valdemar's Itinerary from Utlängan (Sweden) to Reval (Estonia) where the route follows the Swedish coastline in earnest (Varenius 1995:189-194). Adam of Bremen's late 11th century ecclesiastic history, on the other hand, listed only the main descriptive elements of a sea voyage: the departure point, the destination, and the time spent in reaching the destination (Adam of Bremen II, 22, in Schmeidler 1917:80).

The situation becomes even more difficult when addressing the problem in the Viking Age period (8th to 11th century AD), for which very few written sources are available for the interested scholar. One such source is the account of Wulfstan, from the late 9th century AD Orosian history of King Alfred the Great, containing a short description of a real sea voyage.

> *Wulfstan sæde Þæt he gefore of Hæðum, Þæt he wære on Truso on syfan dagum ond nihtum, Þæt Þæt scip wæs ealne weg yrnende under segle. Weonoðland him wæs on steorbord ond on bæcbord him wæs*
> *Langaland ond Læland ond Falster ond Sconeg, ond Þas land eall hyrað to Denemearcan. Ond Þonne Burgenda land wæs us on bæcbord, ond Þa habbað him sylf cyning. Þonne æfter Burgenda lande wæron us Þas land Þa synd hatene ærest Blecingæg ond Meore ond Eowland ond Gotland on bæcbord, ond Þas land hyrað to Sweon. Ond Weonodland wæs us ealne weg on steorbord oð Wislemuðan. Seo Wisle is swyðe mycel ea ond hio tolið Witland ond Weonodland; ond Þaet Witland belimpeð to Estum; ond seo Wisle lið ut of Weonodlande ond lið in Estmere; ond se Estmere is huru fifteen mila brad. Þonne cymeð Ilfing eastan in Estmere of ðaem mere, ðe Truso standeð in staðe, ond cumað ut samod in Estmere, Ilfing eastan of Estlande ond Wisle suðan of Winodlande. Ond Þonne benimð Wisle Ilfing hire naman, ond ligeð of Þaem mere west ond norð on sae; for ðy hit man haet Wisle muða.[1]* (Alfred's Orosius Chorographia, 20)

The English translation of the text (Bately in press) informs us that Wulfstan sailed for seven days and nights from Haidaby, in the lower Schlei Fjord (in today's Schleswig-Holstein, Germany) to Truso, near the Vistula River mouth (identified archaeologically with Janowo Pomorski, located ca. 4 km south of Elbląg in Eastern Pomerania, Poland) (Figure 1). During the voyage, he had on his starboard side Weonodland, that is the Land of the Wends in southern Baltic, to the port were the islands under Danish overlordship (Langeland, Lolland, and Falster), followed by Bornholm, Möre, Blekinge, Öland, and Gotland (the latter belonging to the Svear).

The text is important for several reasons. Its briefness, composition, and informal content point altogether to a description of a real sea voyage that happened sometime in the second half of the 9th century AD, thus making the text one of the very few sailing narratives of the Viking Age Baltic Sea that survived up to our times.

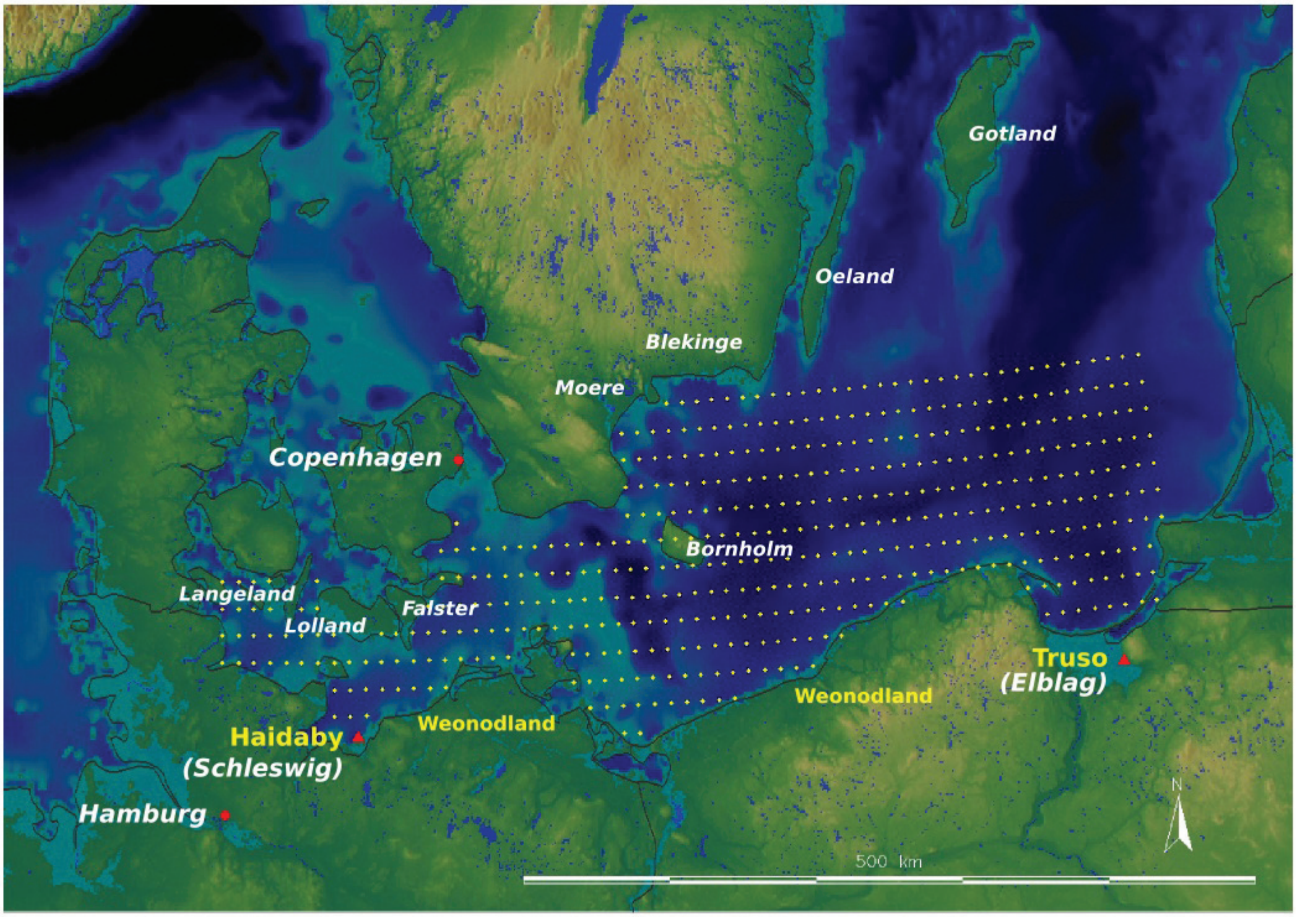

Figure 1. Grid locations (white "+") of wind and current data collected for the Baltic Sea for July 2004; historical place-names are in yellow (Haidaby, Weonodland, Weonodland, Trusco), other place names are white.

Furthermore, its uniqueness lies not only in its narrative power of a sea voyage, but also in the fact that it is mentioning sea travel between two important, archaeologically-documented, trading centers from the Viking Age Baltic: Haidaby (Haithabu) and Truso (Janowo Pomorski). Last but not least, the text provides us with informational clues related to the way navigation was accomplished at that time. In the narrative, the author displays a geographical knowledge employing a maritime orientation system with the ship as the central point. That is, he does not orient the coastlines and islands in relation to each other, but in relation to the sailing ship. This contrasts with Alfred's Orosius orientation system(s) (Korhammer 1985:251-269), and is also unique among historical sources in general. Paradoxically, but not unexpected, it is least ambiguous in terms of cardinal directions. When Wulfstan said that the islands under Danish suzerainty were on the port side, and that Weonodland was on starboard all the way until the Vistula mouth, it is clear that his ship sailed on a general course from west to east.

2 The Research Issue

Nevertheless, that is all the text explicitly indicates, and the specific routing is left to more speculative hypotheses like the one envisioned by Crumlin-Pedersen in 1983 (1983:32-44). Relying upon iconographic evidence from the Bauyeux Tapestry and other medieval historical sources, Crumlin-Pedersen pioneered a novel conceptual approach to early Medieval Norse navigation that emphasized the importance of depth sounding. He suggested that Wulfstan used sounding to follow a pre-selected bathymetric line (he proposed using the –10 or –20 m depth lines) running along the southern Baltic coastline, from the mouth of the Schlei to the mouth of the Vistula (1983: 42-43). In other words, Crumlin-Pedersen argued that the primary orientation system for the Viking Age navigator was below the waterline and not above it, and that coastal sailing was the main type of navigation knowledge for that period. Besides the fact that the author used iconographic and historical sources reflecting a post-Viking Age reality, the proposed construct conflicts not only with the Wulfstan's textual information, but also with the character of his voyage. His sea voyage was routine sailing, which required neither sounding navigation nor coastal sailing, and this statement is supported not only by the historical text itself but also by the following arguments:

1. As a method of orientation at sea, sounding was documented in Northern Europe later in the Middle Ages, although it was known since Herodotus' times in the Mediterranean region. And when documented, sounding is mentioned only in relation to landing or approaching a coastline.

2. The route of Wulfstan could not have followed a specific isobath line since a high resolution DBM of the Baltic Sea bottom clearly shows the sinuosity of these lines. In fact, the route that Crumlin-Pedersen proposed crosses several of these isobaths representing some tens of meters in depth variation—an unlikely route for a navigator supposedly following a constant depth.
3. Crumlin-Pedersen's route also puts an important island, Fehmarn, on the port side. But this is not mentioned in the Wulfstan text. Furthermore, Fehmarn was a part of the Wendland until the mid-12th century and was not mentioned by Wulfstan together with the isles under Danish suzerainty to the portside. In the last decades of the 11th century, Adam of Bremen considered Fehmarn integral part of the Wendish lands:

   > Quarum prima Fembre vocatur. Haec opposita est Wagris, ita ut videri posit ab Aldinburg, sicut illa, quae Laland dicitur. [..] Ambae igitur hae insulae pyratis et cruentissimis latronibus plenae sunt, et qui nemini parcant ex transeuntibus. Omnes enim, quos alli vendere solent, illi occidunt. (Adam of Bremen IV, 18)

   (For early medieval Slavic settlements and artifact distribution see Hucke 1938:4-43, also Harck 1988:299-314).
4. Since land was in view but sufficiently far away all the way up to Arkona and Bornholm, soundings were not necessary for orientation, not even during night sailing.
5. Wulfstan's voyage did not have an exploratory character.
6. Wulfstan underlines in his account day and night non-stop navigation, which implies sailing away from the coastline. Night sailing close to the coastline and without navigational aides imposes considerable risks even today because, while most of the Baltic Sea bottom is covered by 'till' (boulder clay) and sand, it has stony grounds "on the banks and shoals and particularly where exposed to wave action," and "[o]ther than boulders or stones, solid rock is seldom exposed on the sea bed except near the shore" (Baltic Pilot 2002:40). This natural occurrence and the presence of strong coastal currents, which endanger even modern coastal navigation, especially on the long, flat Polish coast would have given Wulfstan little chances for reaching his destination if he would have chosen the coastal routing. Referring to modern ships, the Baltic Pilot (2002:337) states:

   > With persistent winds a rate of about 2 kn (100 cm/s) may be experienced, being strongest about 4.5 Nm offshore. With onshore winds and a swell from the NW, a dangerous S set may prevail. Statistics over the last 60 years demonstrate that 25% of all incidents involving vessels grounding offshore, particularly between Świnoujście and Jaroslawiec, about 87 miles NE, were caused by lack of appreciation and allowance for currents. With onshore winds it is advisable to keep well offshore until the weather improves before attempting a landfall. (Baltic Pilot 2002:337)

If Wulfstan sailed non-stop for seven days and nights, and the shortest linear distance between departure and arrival points is 390 nautical miles (Nmi), the average minimum speed of his vessel was 2.3 knots (or 55 Nmi for a 24-hour day). The more the vessel departed from this straight-line route, the longer the distance it would have travelled and the greater the average speed would have been needed to be to make the voyage in the recorded seven days. Although we do not know Wulfstan's actual travel speed or his routing, the historical account does provide a set of geographical and temporal constraints within which the voyage took place. Thus, the northern sailing boundary is defined by the southern limits of the Danish archipelago, while the southern sailing boundary follows the southern coastline of the Baltic, including its affiliated islands. In navigational parlance, the Danish isles must remain on port while the Wendish (Slavic) lands would always stay on the starboard side. This means further that the historical voyage was of a "corridor-sailing" type, for the Western Baltic at least (up to Cape Arkona, the north-easternmost tip of the Rügen Island) (for details see Indruszewski and Godal in press).

In order to go beyond the basic understanding of the text, and also to keep highly speculative constructs at bay, we employ GIS-based simulation as a new way to develop more explicit and testable hypotheses about Wulfstan's sea route from the meager historical information. The simulation presented here does not operate on fictitious values, but it is based both on the historical information provided by the Wulfstan's account and on the real-time data provided by experimental archaeology.

In order to use the data provided by experimental archaeology, sailing voyages replicating Wulfstan's routing have to fulfill several strict conditions, such as: the experimental voyage has to be carried out exclusively through the use of natural propulsion (wind, currents, human power); the voyage has to be carried out from Haithabu to Janowo Pomorski in order to replicate fully the distance traveled by Wulfstan; the voyage has to be carried out non-stop both during daytime and night time in order to replicate Wulfstan' information; and the voyage has to be carried out without the help of modern navigational aids, including sea charts and compass. An earlier attempt to sail a hypothetical route of Wulfstan's voyage, taken by the Danish Marine cutter Barsø in 1993, cannot be used for our simulation since it did not fulfill any of the above-mentioned conditions.

In the summer of 2004, a replica of the 11th century Skuldelev 1 vessel , *Ottar*, reached Gdańsk, Poland from Schleswig, Germany, in a little over four consecutive days and nights after sailing a total distance over ground of 390 Nmi (Englert and Ossowski, official communication Wismar 28 September 2004). Although this voyage did not fulfill most of the conditions required of a real experimental voyage (the crew used modern navigational aids, the ship was sailed under motor in the Schlei and in Gdańsk and also stopped at anchor for the first night of the voyage, etc.), the *Ottar*'s real-time sailing data, its open sea routing, and the wind & current conditions were used in our GIS-based simulations to emulate the conditions from the real-world of sailing, inasmuch as the sailing capabilities of the vessel and the crew were the closest approximation one can presently get for replicating the 9th-century sailing itinerary of Wulfstan. The *Ottar* voyage was carried out as a result of a larger research project directed by Indruszewski at the Viking Ship Museum aimed on the theoretical and practical reconstruction of Wulfstan's 9th century voyage. The initial plan of sailing the distance Haithabu-Janowo Pomorski with a small-size historical replica was cancelled because of the crew's psychological and physical unpreparedness to reconstitute the sailing conditions characteristic of 9th century AD navigation.

Replicated voyages and computer simulation have been used in other settings to help test the feasibility of proposed hypotheses about sea voyages, and to generate new ones in a systematic way (e.g., Heyerdahl 1950; Irwin 1992; Irwin et al. 1990; Levison 1973). In addition, several modeling simulations were proposed for determining the best sailing routing on the open seas. The stochastic modeling for onboard application during yacht racing is one of them (Allsopp 2000). Yacht possible routing is shown in the stochastic modeling as arcs delimited by node-time-scenario triplets. The most important assumption of the stochastic modeling is the perfect knowledge of weather. Therefore, weather data is required for input for each scenario at each node. The resultant routing takes the shape of an ellipse that includes all possible routes for the given weather pattern. Another simulation is that presented by T. Veldhuizen, which strives to present a dynamic modeling for optimal sailing (T. Veldhuizen 2001). The basic tools of dynamic modeling are discretization of sailing paths and transit time functional, represented graphically as edges (sailing paths) and vertices (transit time t0-tn). However, the sailing routes are calculated with the wind field assumed to be invariable, and without taking into account other sailing factors such as currents.

While our focus in this presentation is on computer simulation, both methods have been applied to developing a basis for a more accurate reconstruction of Wulfstan's voyage and for studying Viking seafaring more generally. Through this presentation, we suggest thus, an alternative and complementary means of testing and generating hypotheses about ancient sea voyages through computer simulation modeling. While this has generally been done through customized software, it could be more widely employed by archaeologists and historians if easily available, off-the-shelf packages could be used. Modern GIS software includes tools for simple modeling of movement across space. Here, we present the initial results of using two types of such GIS tool sets to simulate Viking seafaring, using Wulfstan's voyage as a test case. Real-time sailing data, including routing and wind conditions, collected during the *Ottar*'s replicated voyage in 2004 were used to evaluate the GIS-based simulations. We compare sailing routes generated by a least-cost path (LCP) routine in ArcView 3.1 (ESRI) and an anisotropic spreading routine (AS) in GRASS 6 GIS (open source) with both the historical information and the real-time data from the replica voyage from Schleswig to Gdańsk.

3 Research Methods

As already mentioned, we employ two GIS methods for modeling movement across surfaces to simulate Viking Age sailing, and for both modeling tests, we focus on wind intensity (i.e., velocity) and direction as the primary drivers of a sailing vessel. Currents, although relatively weak in the Southern Baltic, also would have affected sailing routes in that period. At this point, however, we chose not to include currents in our simulation. The main reasons for this decision were that we do not have clear information about currents affecting *Ottar*'s voyage in 2004 as we do for wind, and more importantly is that the algorithms used in each GIS method of computation do not permit the incorporation of a second force vector to drive movement (though either could be extended to do so). Below is a brief overview of each simulation method.

LCP modeling has been used extensively in GIS applications for identification of optimal routing based on user-defined criteria. Optimal routing seeks to minimize travel costs between an origin point and destination point across a terrain where movement can be affected (encouraged or impeded) by variables such as slope, vegetation, urban attributes, and water vicinity. In applying LCP to a sailing voyage, a trailing wind is treated conceptually like going downslope on a topographically variable terrain, while a headwind is treated like travel upslope. In brief, the LCP procedure, as implemented in GIS, involves the following steps:

1. Create one or more cost surface raster grids, where the value of each grid cell represents the absolute or relative costs of (or resistance to) movement at every location in the research area. In our case, this is derived from wind velocity.
2. Create an accumulated cost distance grid, where each cell represents the total costs of travel (based on the combination of all relevant cost surfaces) from a starting location (source or origin point) to all other locations in the study area.
3. Optionally, create a backlink grid (cost direction surface) from the accumulated cost surface that indicates the directionality of travel costs in each grid cell (e.g., it costs more energy to travel upslope than downslope). We use wind direction in this calculation (i.e., a tailwind decreases movement costs while a headwind increases them).
4. Calculate a path that minimizes total costs (LCP) from the source to a desired end location (the destination) across the accumulated cost surface. This path is the modeled sailing route.

Anisotropic spreading (AS) is less well known than the LCP analysis. It models the spread of a phenomenon across a terrain from a point of origin. Perhaps the most common usage of AS procedures in GIS is in modeling the spread of wildfires. The rate and extent of spreading for a wildfire can be affected by topography and forces like wind that have both intensity and direction, causing it to spread unequally in different directions (e.g., faster downwind and uphill). It might seem odd, at first, to use modeling algorithms most widely used for fire to simulate travel across water. However, in some ways, it may be more realistic than LCP. Conceptually, a vessel is treated as a specific point on a fire front that is driven by wind of variable velocity and direction, over a given time period. The AS routine also can calculate a backtrack from any given point on a fire front to its point of origin, tracing the route it took under variable environmental (i.e., wind) conditions.

The AS routine in GRASS is optimized to model the behavior of wildfires (Jianping 1994). Hence, as input, it requires information about parameters that commonly affect wildfires: the speed and direction of the wind, the slope and aspect of the topography, and characteristics of the vegetation that is burning. In order to use this routine to model a wind-driven sailing vessel traversing the Baltic Sea, we used a level plane topography and chose grassland for vegetation. In spite of waves at local scale, the sea approximates much more closely a plane than a hilly or mountainous terrestrial landscape. Fire spreads variably across space in forest and woodland, depending on such parameters as moisture content, amount of downed wood, and relative densities of arboreal and shrub vegetation. Grass, on the other hand, burns quickly and evenly in all directions across a level plane except as influenced by the wind, as would be expected for wind blowing unimpeded across the sea surface. As developed in GRASS, AS modeling involves three major steps:

1. Using a series of raster maps that represent the parameters that influence the spread as values for each grid cell (e.g., maps of wind direction and wind velocity), derive three raster maps showing the maximum rate of spread (ROS) in the primary direction of spread (i.e., downwind in our case), the direction of the maximum ROS, and the rate of spread (ROS) perpendicular to the primary direction of spread (this has no impact in our example here but is required for subsequent steps).
2. The three ROS maps produced in the first step are then used to model the spread phenomenon (in this study, wind-driven sailing routes). This second step produced a graphic simulation of the anisotropic spread, a map of the cumulative duration of spread, and a map containing the backlink information.
3. In the third step, the backlink map is used to calculate the most probable spread path from the origin point to the destination. This is the modeled sailing route for the example presented here.

In order to make our simulations more realistic, we constrained them to the possible water routes that Wufstan could have taken. We set all land areas—island and continental—to null value masks so that the costs surface for LCP and spread maps for AS routines would be limited to the grid cells over water and extending eastward from the western coast of Denmark to east of the Vistula River mouth. We used wind data encountered by *Ottar* in its 2004 Baltic voyage for this test of GIS-based simulation methods. Wind speed and direction measurements were collected for every 10' of latitude and longitude across the Baltic Sea between 54º and 56º N and 10º and 20º E for the duration of the *Ottar*'s voyage (Figure 1).[2]

These measurements were then re-projected to UTM Zone 32 and interpolated to continuous raster grids of wind speed and direction at a 1-km resolution (Figures 2 and 3), using regularized spline tension in GRASS 6 (Hofierka et al. 2002; Mitas and Mitasova 1999), that were subsequently used for LCP and AS modeling.

3.1 The AS Sailing Simulation in GRASS

The AS routine models the spread of phenomena over a given surface during a given period of time, taking into account the effects of spatial heterogeneity in local conditions on the unevenness of spreading (i.e., anisotropy) in different directions. Here, relevant spatial heterogeneity included wind velocity, wind speed, and the distribution of land and water. As described above, wind data collected during the *Ottar*'s voyage was interpolated to raster maps of wind speed and wind direction. The interpolated raster maps of wind speed and direction extended to a 20-km buffer beyond the original data grid to minimize edge effects in the subsequent modeling. Then, a DEM of the Baltic area, interpolated in GRASS from a file of elevation points for the region (Seifert et al. 2001), was used to mask out the land area out of the wind speed and wind direction raster grids. In this manner, all modeling was restricted to those parts of the Baltic Sea relevant to the voyage.

As noted above, the simulation was done in three major steps, by using the AS module for Wildfire modeling in GRASS 6. For surface topography, we created a level plain DEM to represent the Baltic Sea surface. Wind velocity had to be converted from m/s to ft/min for the modeling routine. For the required vegetation input, we empirically tested several U.S. Forest Service fuel models (Rothermal 1983) with varying degrees of success before settling on a grassland model, as noted above. These fuel models are based on burning parameters of different vegetation communities, including: the mass of fuel per unit area (fuel loading), fuel depth, fuel particle density, and the heat of burning for each fuel. We tried timber (fuel model 10), brush (fuel model 5), chaparral (fuel model 4), and tall grass (fuel model 3). We used default USFS values for one hour fuel loading and live moisture. Slower burning models (e.g., timber) spread more evenly in all directions rather than the primary wind direction at the wind speeds of the *Ottar* voyage. Many failed to spread across the Baltic Sea to the eastern edge of the study region, even when we weighted the primary rate of spread (ROS) before using it in the spread simulation analysis. On the other hand, faster burning fuel models (e.g., tall grass) better modeled sailing because they spread most rapidly in the main wind direction and were better able to spread across the entire study region. The fuel model we used was input as a constant across the whole study region (rather than as a map of spatially varying vegetation).

The most successful simulation used the tall grass fuel model (3) with standard values of 3% for one hour fuel loading and 0% for live moisture (Figures 4-6).

However, it was still necessary to multiply the maximum ROS and base ROS by 10 in order to create a model that would spread across the entire Baltic study area, a much larger area than that of a normal wildfire (Figures 7-9). These

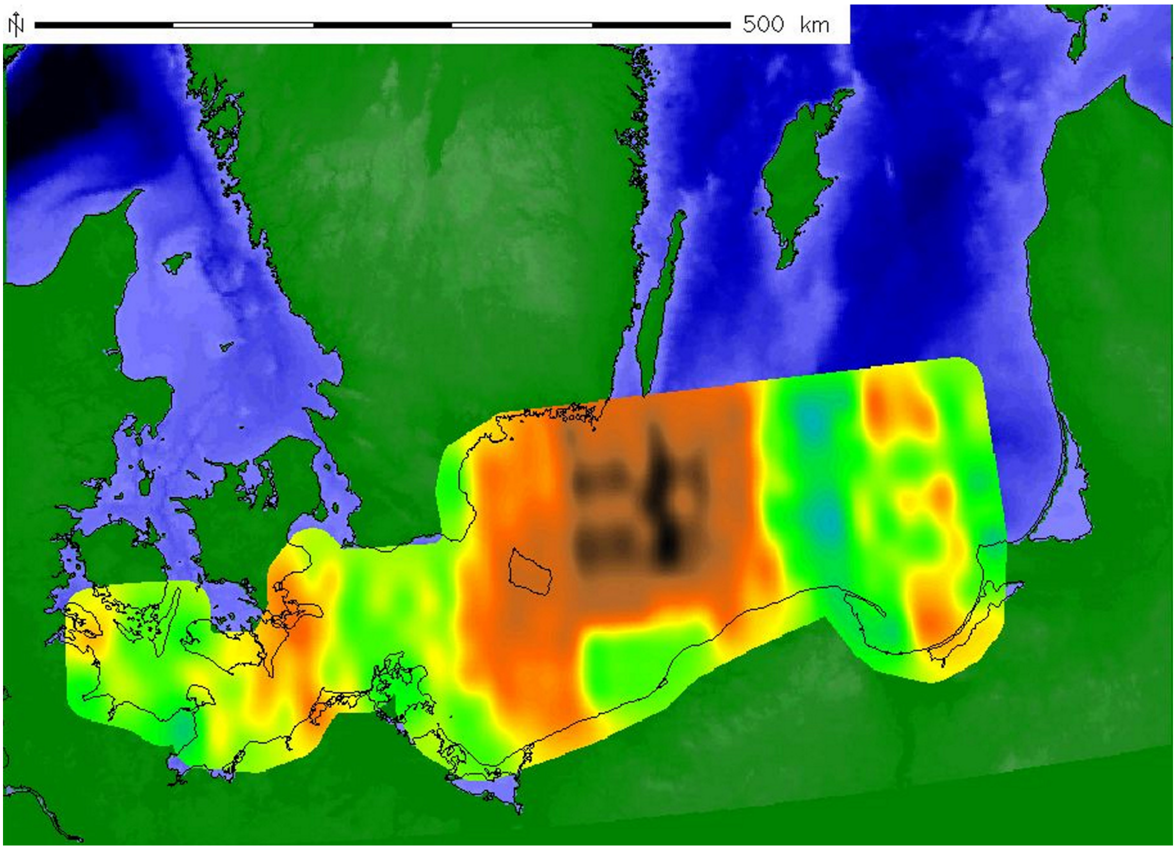

Figure 2. Wind speed raster grid map (shaded zone extending eastward from southeastern Jutland) interpolated from 10' data points in GRASS 5.7. Lighter is lower velocity and darker is higher velocity.

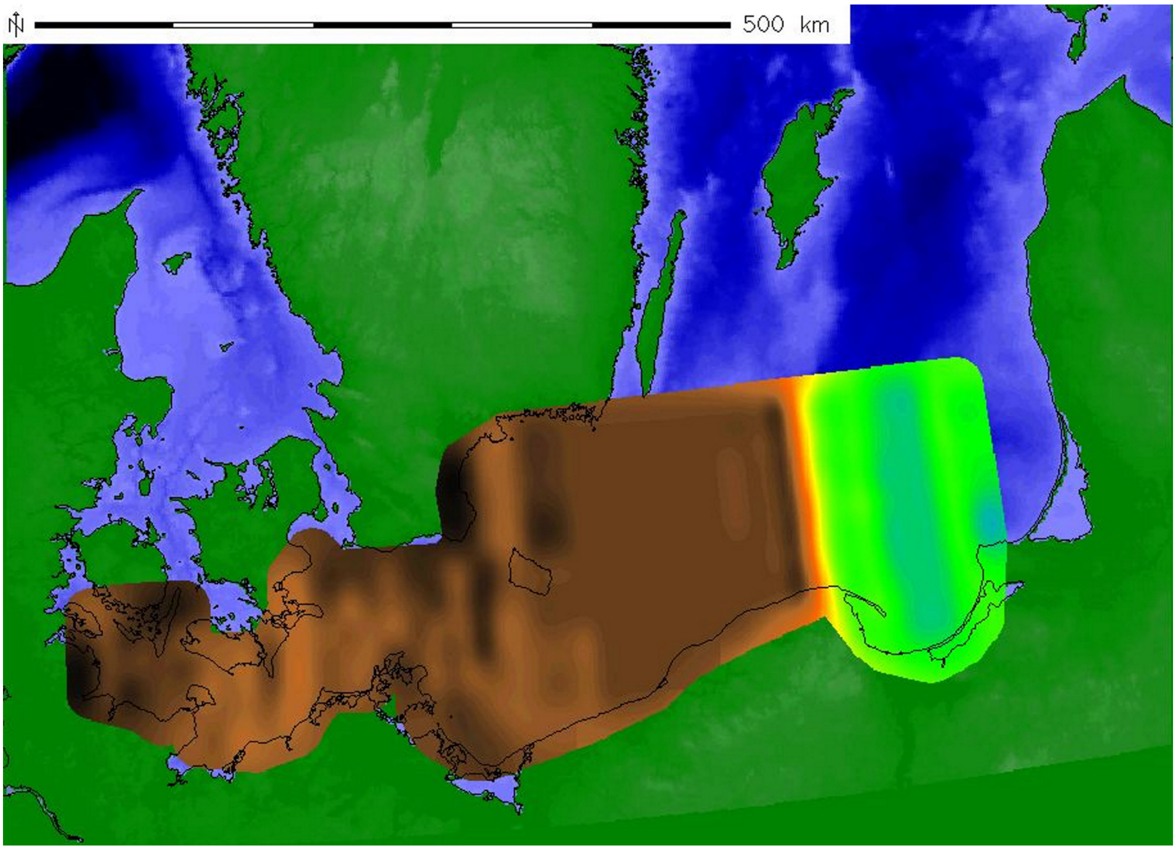

Figure 3. Wind direction raster grid map, interpolated from 10' data points in GRASS 5.7. Lightest is an east wind, darkest is a west wind, and light brown-yellow (medium gray) is a southwest wind.

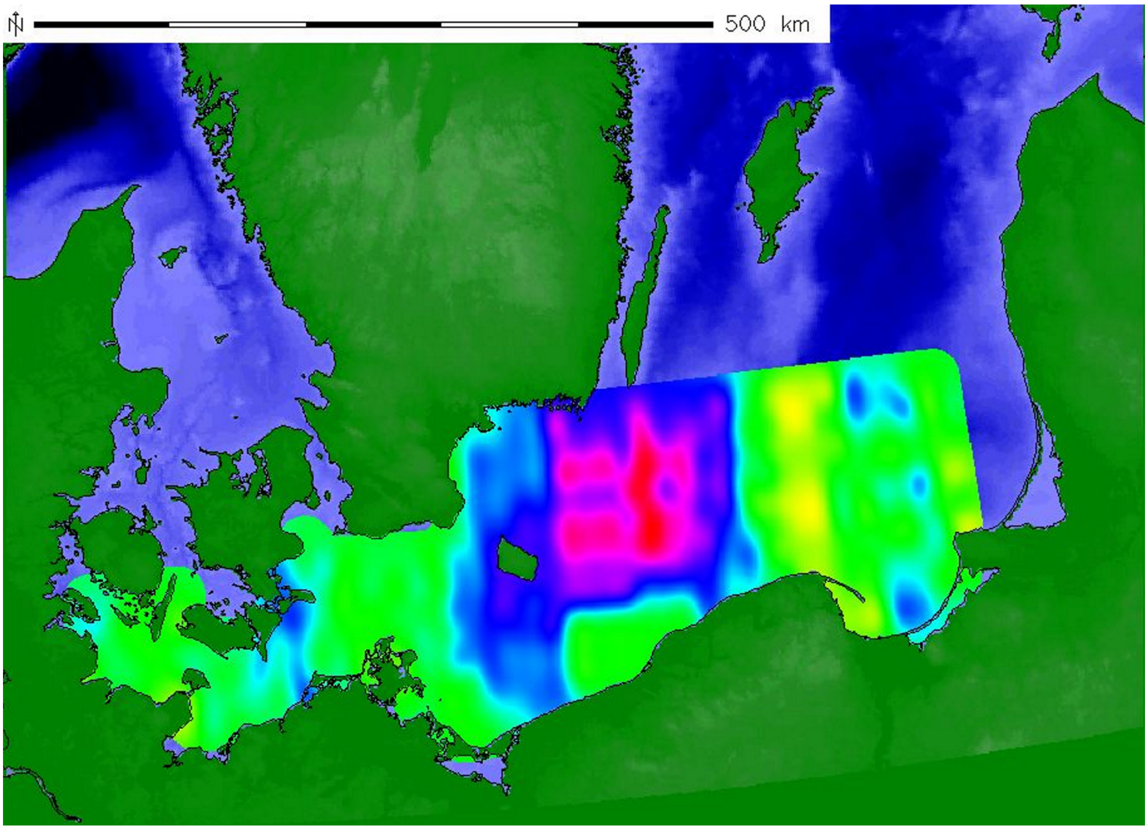

Figure 4. Maximum rate of spread (ROS) calculated in the GRASS 5.7 anisotropic wildfire spreading module with wind as the primary spread-generating parameter. Lightest is fastest and darkest is slowest.

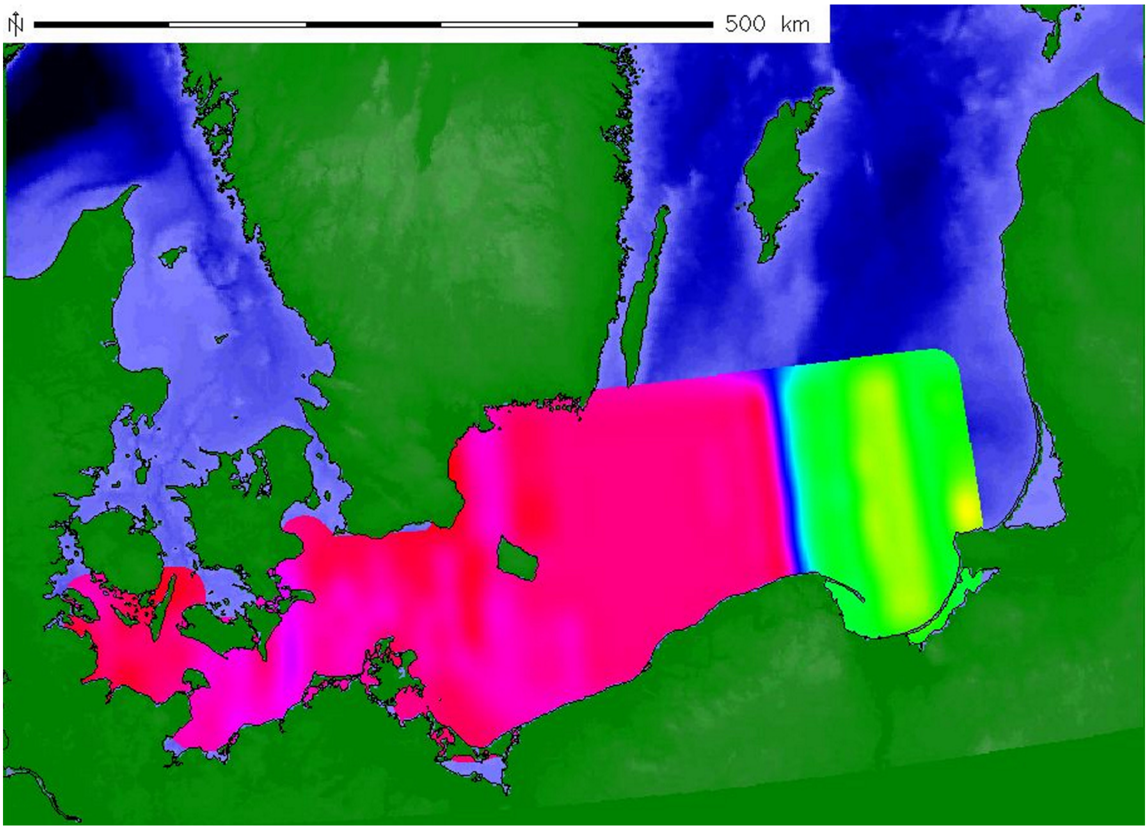

Figure 5. Direction of maximum rate of spread (ROS) calculated in the GRASS 5.7 anisotropic wildfire spreading module with wind as the primary spread-generating parameter. Lightest is an easterly spread, darkest is a western spread, and medium grey is a northwestern spread.

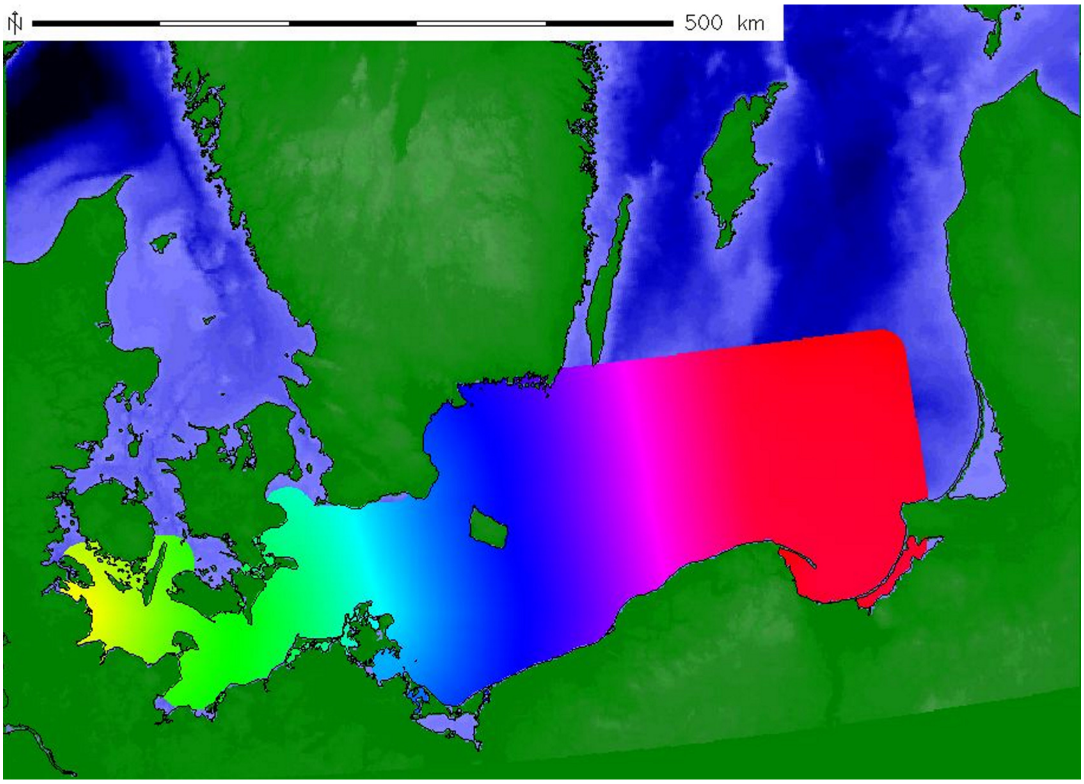

Figure 6. Cumulative spread time calculated in the GRASS 5.7 anisotropic wildfire spreading module. Time runs from lightest to darkest.

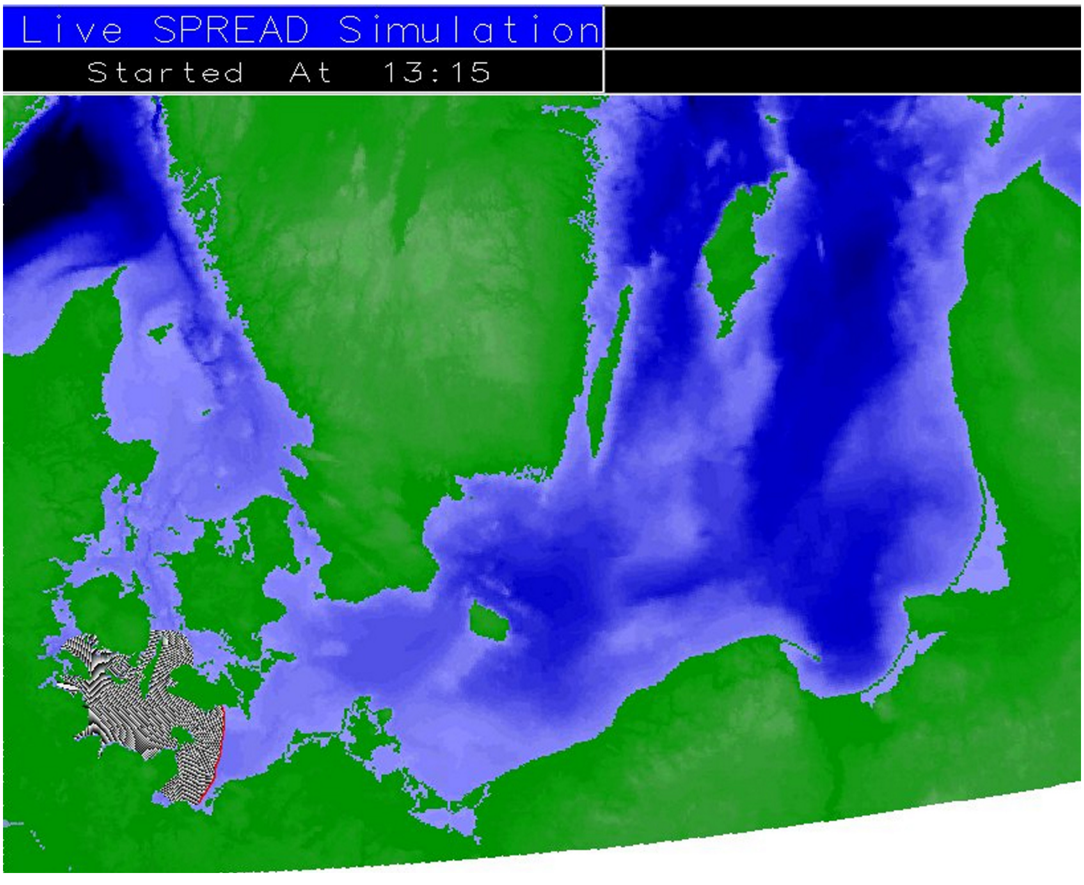

Figure 7. Screen shot of wind-generated spread simulation generated by the GRASS 5.7 anisotropic wildfire spreading module. Spread is shown as patterned area beginning at the southeastern coast of the Jutland peninsula and extending progressively eastward.

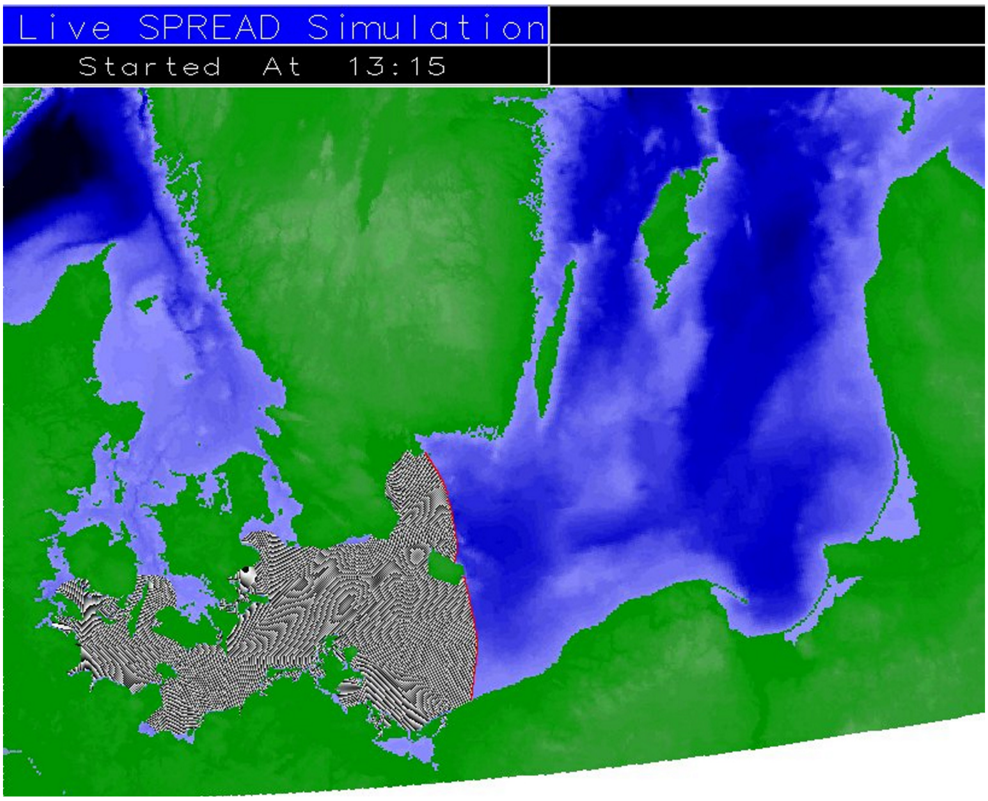

Figure 8. Screen shot of wind-generated spread simulation generated by the GRASS 5.7 anisotropic wildfire spreading module. Spread is shown as patterned area beginning at the southeastern coast of the Jutland peninsula and extending progressively eastward.

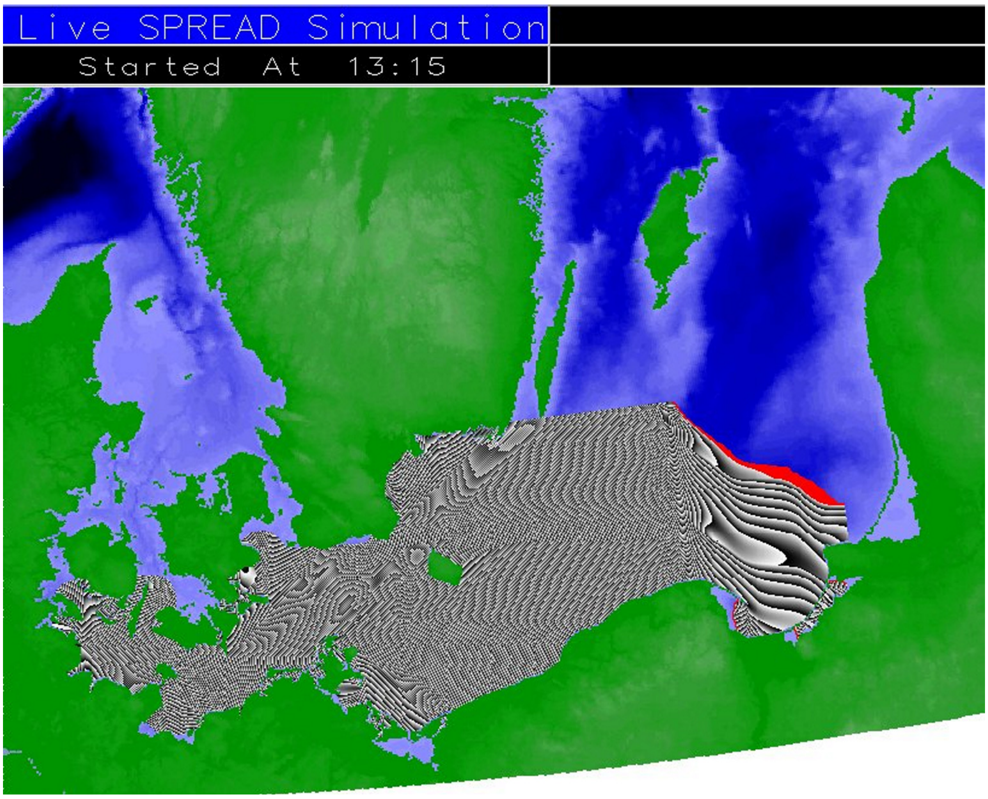

Figure 9. Screen shot of wind-generated spread simulation generated by the GRASS 5.7 anisotropic wildfire spreading module. Spread is shown as patterned area beginning at the southeastern coast of the Jutland peninsula and extending progressively eastward.

issues are related to the specific wildfire implementation of the AS routine in GRASS rather than considerations about the usefulness of the underlying AS algorithm.

The starting point of the anisotropic spread was set at the mouth of the Schlei Fjord in northern Germany at 54° 41 lat N, 10° 02 long E. By setting all input variables except wind to constants, the GRASS wildfire routine produced a resultant raster grid of the spread and associated backlink grid based on the wind velocity and direction in the study area. This approximates the likely paths taken by a simple sailing vessel outward from Schlei Fjord given the weather conditions recorded during the *Ottar*'s voyage in 2004.

3.2 The LCP Sailing Simulation in ArcView

The LCP simulation was made more difficult because ArcView normally requires a single digital elevation model (DEM) of topography, from which it calculates cost intensity and cost distance from the slope, and cost direction from the aspect. We tried various methods for combining wind speed and direction into a single "DEM" of sailing conditions without success. On the other hand, multiple cost variables or cost direction variables could be combined easily. For example, combining wind direction and current direction produced apparently meaningful results (Figure 10) from the mouth of Schlei Fjord eastward across the Baltic. This avenue needs more research in order to be used in subsequent simulation to more accurately model the parameters affecting sailing.

Although the ArcView normally expects a single DEM, it is possible to input two separate grids representing cost intensity and cost direction. We followed this approach setting wind strength as the cost intensity (equivalent to slope calculated from a DEM) and wind direction as cost direction (equivalent to aspect calculated from a DEM). As with the AS analysis in GRASS, we set all land grid cells equal to null so that the LCP analysis would only take place on sea grid cells (Figure 11). ArcView calculated an accumulated cost-distance map from wind velocity without difficulty (Figure 12). However, using wind direction (Figure 13) as cost direction was considerably more problematic. Intuitively, wind direction values should be 180° from an aspect value from a DEM needed for LCP analysis. This is because a wind from the west will reduce the cost of a vessel traveling towards the east, equivalent to traveling downslope on an east-facing slope. Surprisingly, creating a cost direction grid in this way did not have the desired result, but produced completely meaningless least-cost paths—such that no path from Schlei Fjord to the Vistula River mouth could be calculated. After additional testing, we discovered that if we used a normal wind direction raster map and allowed ArcView to create a cost direction grid from this map (i.e., another cost direction grid), we were able to achieve a meaningful least-cost path when this direction grid was combined with the cost-distance map created from wind velocity (Figure 14).

The results of the LCP analysis closely match both the

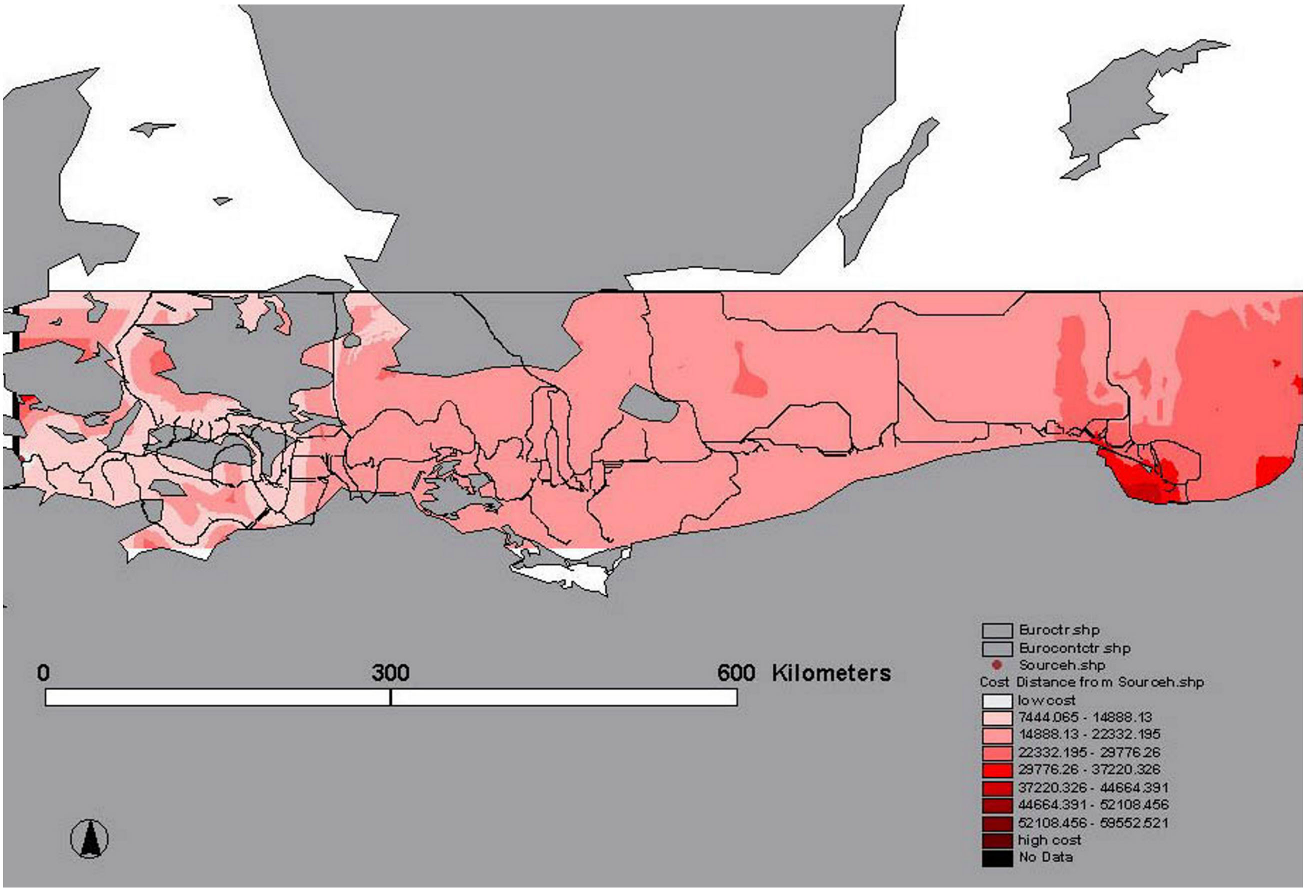

Figure 10. Combined wind and current direction raster map, generated by the ArcView 3.1 least-cost path routine.

AS analysis and the actual path of *Ottar*, intuitively suggesting that they are correct—given wind velocity and direction as the only variables for the analysis. However, the final cost direction grid used in the LCP analysis was created from another cost direction grid (i.e., wind direction) by an undocumented ArcView routine. The ArcView results are counterintuitive given the inputs. Further, the ESRI software is proprietary, preventing examination of the underlying code, and there is no documentation in ArcView of the kinds of values needed in a valid cost direction grid. We tested various possible combinations of values for cost direction—including ones that seemed that they should be correct—and all except the method described here gave spurious results. Hence, we recommend caution when using this routine until it has been tested further or properly documented.

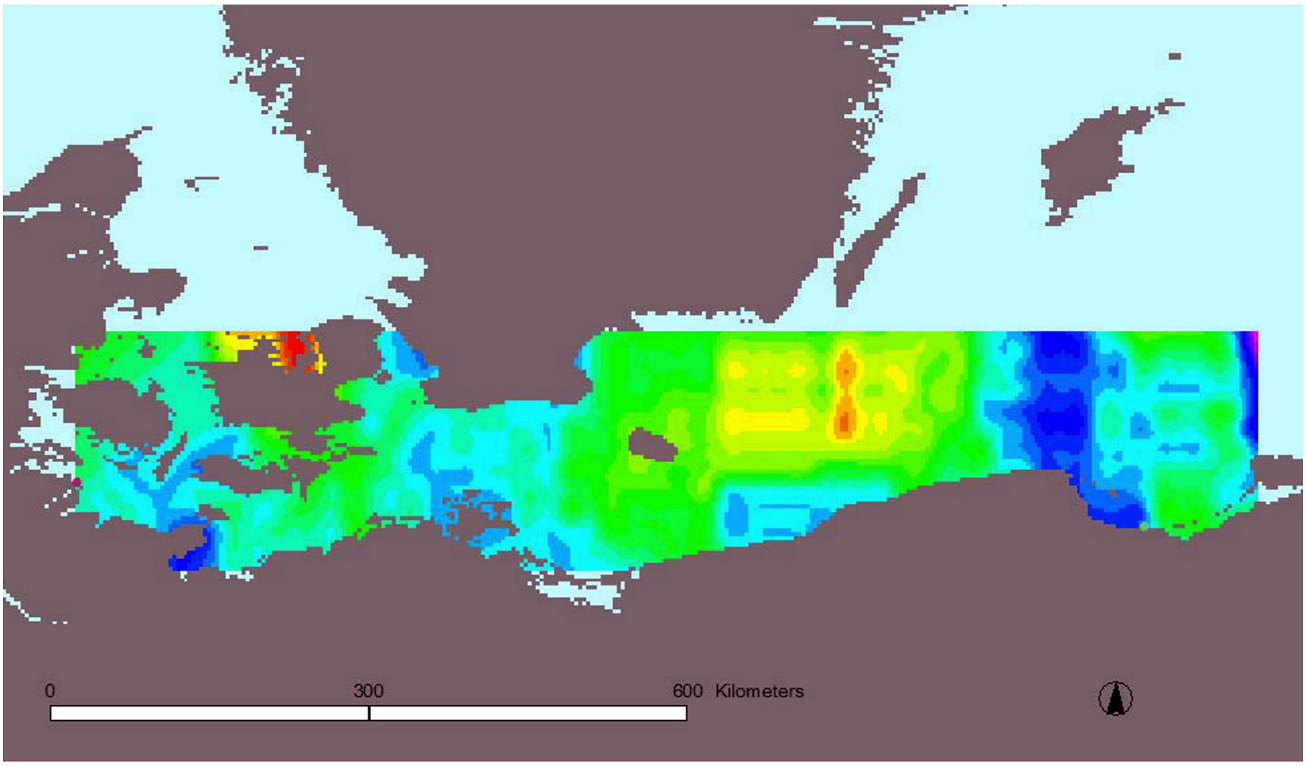

Figure 11. Cost surface based on wind velocity generated by the ArcView 3.1 least-cost path routine. Lightest is lowest cost and darkest is highest cost.

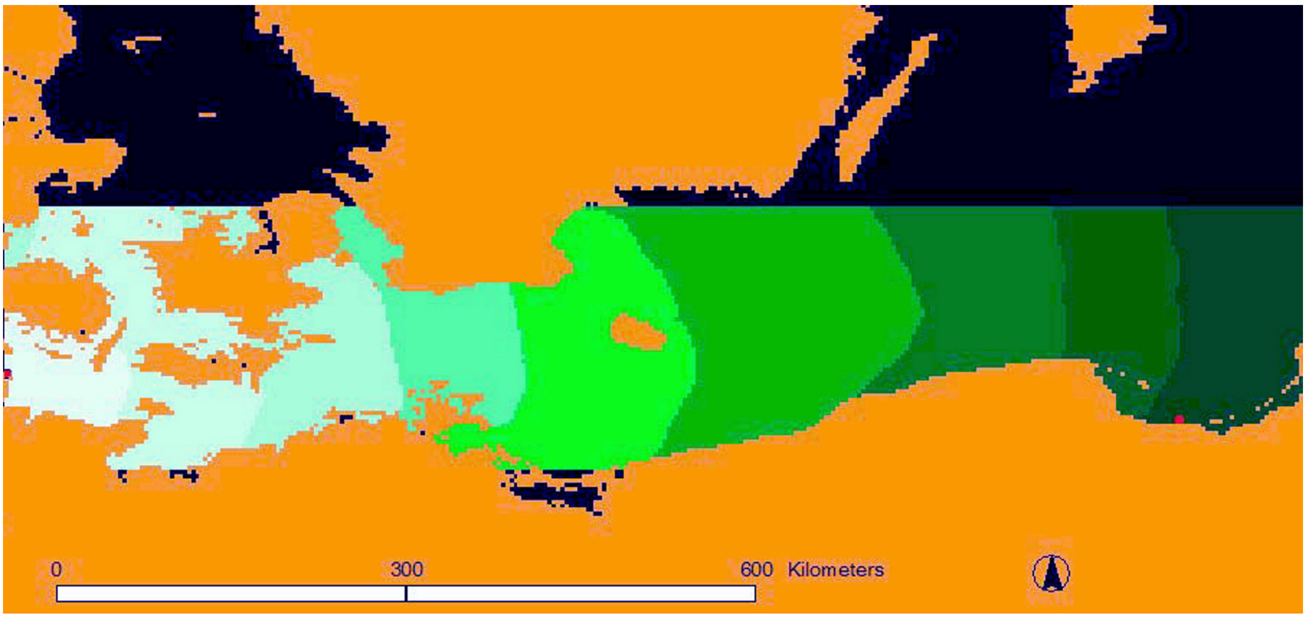

Figure 12. Accumulated cost distance grid generated by the ArcView 3.1 least cost path routine. Lightest is lowest cost and darkest is highest cost.

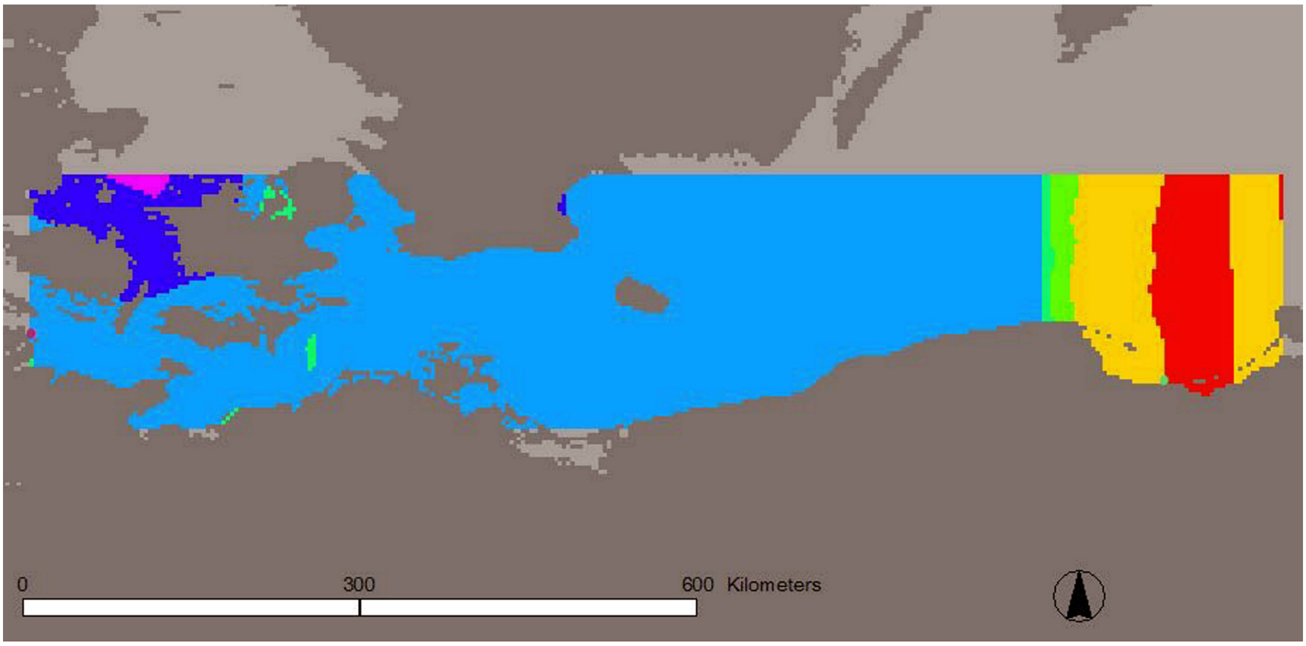

Figure 13. Wind direction grid generated by ArcView 3.1. Lightest is easterly wind and darkest is westerly wind.

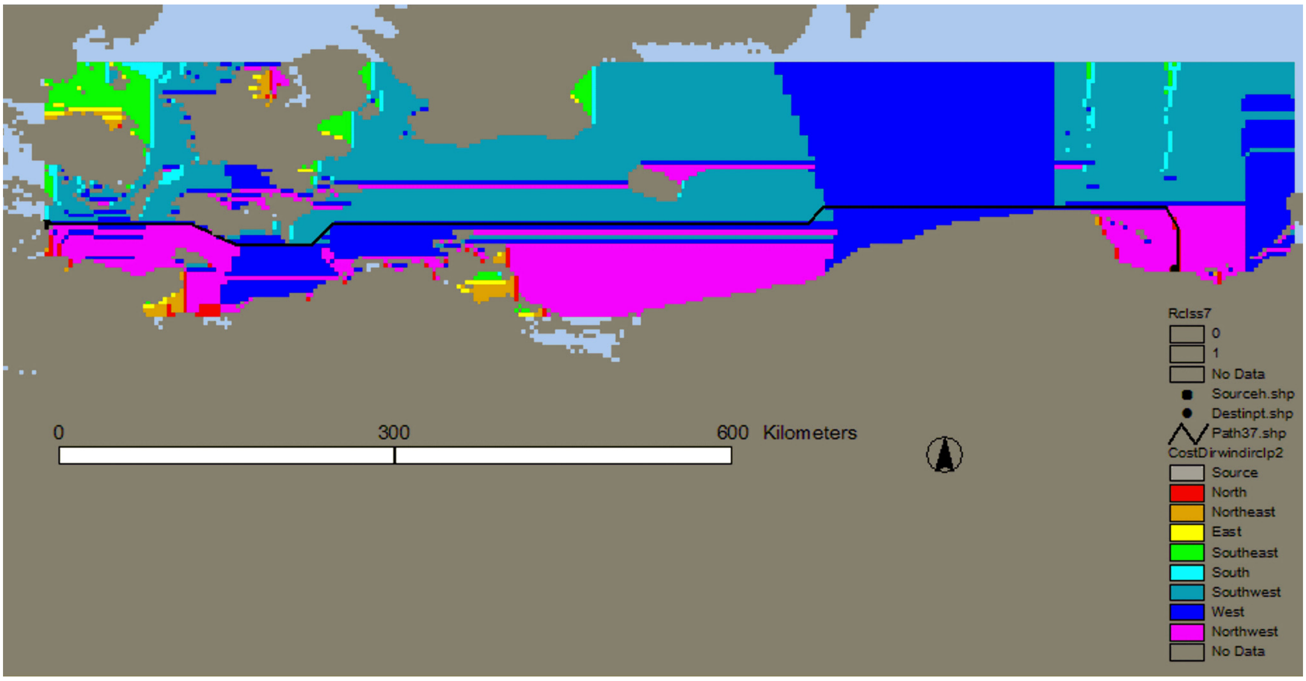

Figure 14. Backlink least-cost path analysis grid generated by the ArcView 3.1 least cost path routine. Black line traces the least cost path from Schlei Fjord to Gdansk.

4 Discussion

The final step in both GRASS AS and ArcView LCP analyses was calculating a most likely (AS: red line) or least-cost (LCP: green line) sailing route from Schlei Fjord, Germany to Janowo Pomorski, Poland. These routes are shown in Figure 15, along with the route of the 2004 *Ottar* voyage (yellow line). Both simulations closely match the actual route of the *Ottar*, navigating off the southern coastlines of Lolland and Langeland, southern tip of Falster, and around Bornholm's southern shores, before heading eastward across the open Baltic.

The AS routine in GRASS 6 seemed to track more closely a sailing route influenced mainly by wind conditions than did the ArcView LCP routine. The change in wind direction at the foot of the Hel Peninsula caused the path to veer towards the northeast, which would be normal not only for a wildfire but also for a ship propelled primarily by the prevailing wind and whose skipper would be sufficiently skilled to forecast the subsequent wind change. In spite of the cautions expressed above, the ArcView-generated LCP also matched closely *Ottar*'s voyage from Schleswig,

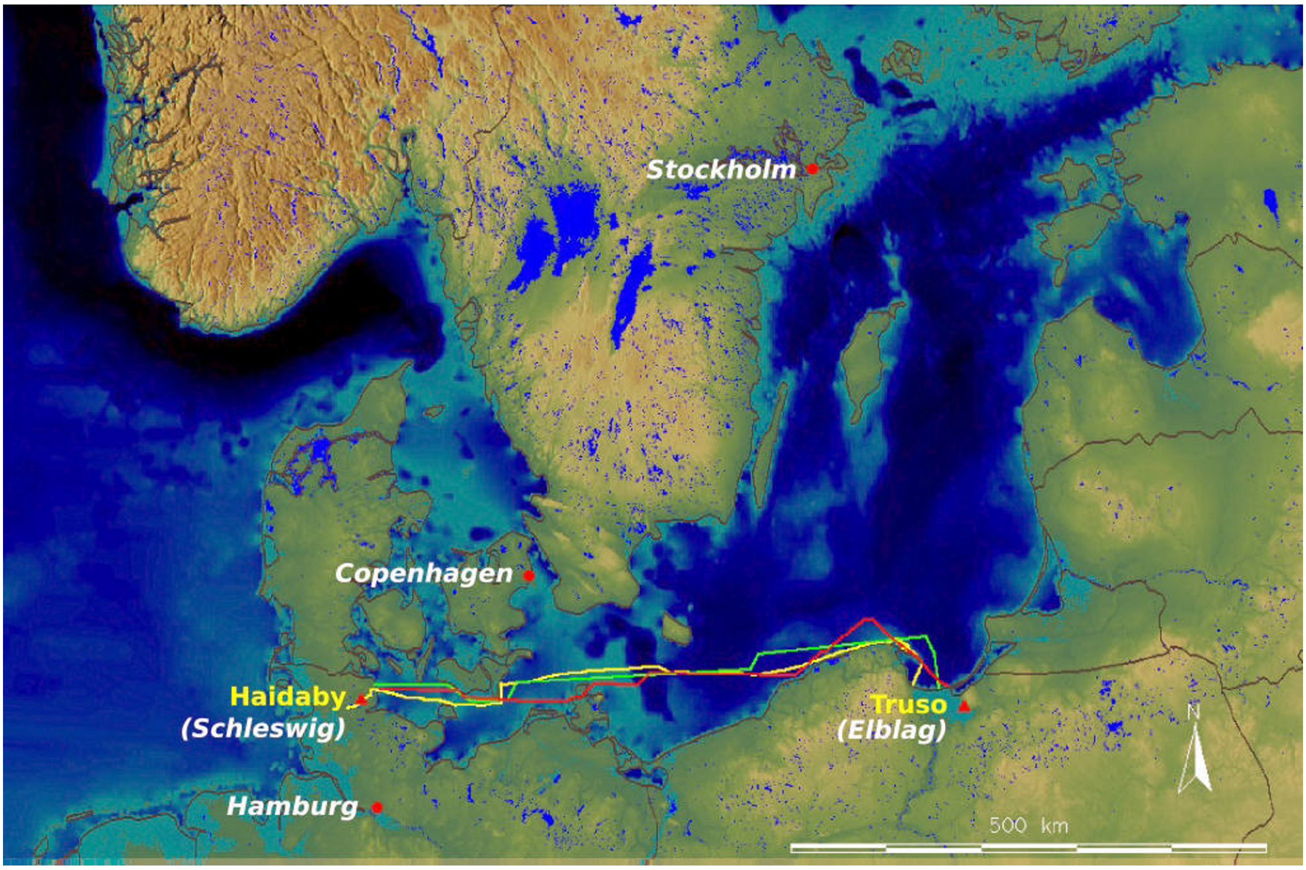

Figure 15. Routing of Wulfstan from Schlei Fjord to Gdansk generated by the GRASS AS wildfire spreading module (red or darkest gray line). Green (medium gray) line traces the ArcView LCP routing of Wulfstan. Yellow (lightest gray) line traces actual route of the Ottar in 2004.

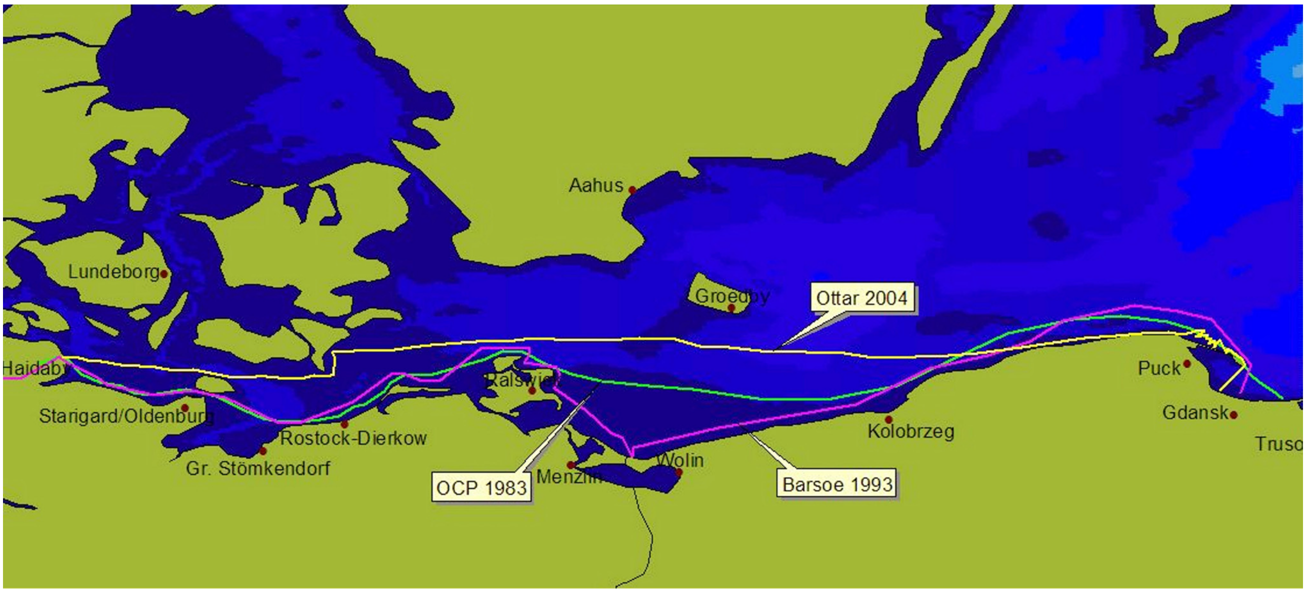

Figure 16. Wulfstan's routing from Schlei Fjord to Gdansk. Route of the Ottar in 2004 is shown in yellow (lightest gray), Barsø's route is shown in violet (darkest gray) and Crumlin-Pedersen's hypothetical route in green (medium gray).

Germany to Gdańsk, Poland—although it seems somewhat less sensitive to shifts in wind direction than the AS routine. The fact that both routines produced similar results that closely match a real voyage, suggests that GIS-based simulation has considerable potential for modeling ancient sailing routes.

As noted previously, and illustrated in Figure 16, three routes have been proposed for Wulfstan's 9th century voyage: a route developed on the basis of historical and archaeological considerations (OCP line for Crumlin-Pedersen

1983), an actual coastal voyage carried out in 1993 by the Danish Navy cutter *Barsø*, which attempted to recreate the OCP 1983 hypothetical route, and the open sea voyage carried out in 2004 by the early medieval ship replica *Ottar*. The next stage of our GIS modeling of Viking seafaring will be to simulate sea routes based on monthly and seasonal average weather conditions in the eastern Baltic in order to better evaluate which of these (or other) routes are more likely. We also hope to be able to incorporate sea current data into our simulation in the future to better account for the combinations of wind and current conditions that affected Viking seafaring. GIS-based modeling is a promising means of recreating the spatial and temporal dynamics of ancient societies from the static remains that make up the archaeological record.

Notes

[1] For English translation, see paper by Janet Bately, Wismar Seminar Proceedings

[2] The following data sources were used in the analysis:

For sea bottom data:

- Seifert, Torsten, Tauber, Franz, Kayser, Bernd: 2001: "A high resolution spherical grid topography of the Baltic Sea – revised edition", *Proceedings of the Baltic Sea Science Congress*, 25-29, Stockholm.
- Bundesamt fűr Schiffahrt und Hydrographie 3021, 3022 (2003/2004)
- Deutsches Hydrographisches Institut, Die Ostsee mittlerer Teil, 1930

For wind data:

- Matthias Ketzel, Danish Meteorological Institute, Risø, Denmark
- Denmark Meteorological Institute. (http://www2.dmu.dk/AtmosphericEnvironment/thor/metindexdk.html)
- Air Resources Laboratory, NASA. (http://www.arl.noaa.gov/ready/amet.html)
- Jet Propulsion Laboratory, NASA. (http://poet.jpl.nasa.gov)
- WindData.com (http://130.226.17.201/site_distrubutions.php?site_code=roedsand&country=Denmark)

For sea current data:

- Bundesamt fűr Schiffahrt und Hydrographie. (http://www.bsh.de/aktdat/modell/stroemungen/Modell1.htm9
- Meteomedia Wetterstationen. (http://wetterstationen.meteomedia.de/messnetz/)

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