individuals are working on projects related to the societal impacts of extreme weather events? The GCIS is intended to be a web-based source of authoritative, accessible, usable and timely information about global change for use by scientists, decision makers and the public. The Semantic Web technology will help make the GCIS a part of the Web of Data, such that other tools and services are also able to interact with data and information in the GCIS. This should enhance approaches applied to address socio-economic, physical, ecological and other intellectual challenges.

Persistent and universally resolvable identifiers, such as DOI (Digital Object Identifier), are widely accepted for research articles and increasingly also for data. ResearcherID and ORCID (Open Researcher & Contributor ID) make literature and data easily accessible and citable, and global change research increasingly benefits from open-access literature and data sets[17]. We argue that the global change research community should take one step further with the curation of provenance information — following the example of the GCIS. These works promote meaningful eScience[18] — the digital or electronic facilitation of science — and wider participation from the global change research community is desired.

Concluding thoughts

As global change information becomes both more abundant and increasingly important, our need to know more about what, how, when, where and why information is produced is becoming ever more necessary. Well-curated provenance information makes scientific workflows transparent and improves the credibility and trustworthiness of their outputs. It also facilitates informed and rational policy and decision-making based on the outputs of global change research. For all these reasons, work on provenance is timely and foundational, and is now an embedded component of the GCIS and a sustainable approach to climate assessment. ❐

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Author contributions

All authors contributed to the planning of the paper. X.M. led the work. P.F. contributed the use-case-driven Semantic Web application method which generated the provenance graph in the global sea-level rise use-case. C.T. participated in use-case analysis and provided suggestions on ontologies to be used. X.M. prepared the figures. All authors contributed to the writing of the paper.

COMMENTARY:

Arctic shipping and marine invaders

A. Whitman Miller and Gregory M. Ruiz

The emergence of new Arctic trade routes will probably change the global dynamics of invasive species, potentially affecting marine habitats and ecosystem functions, especially in coastal regions.

With striking reductions in Arctic sea-ice coverage in recent years[1,2], a long-anticipated opportunity for modern interocean shortcuts is being realized. The first commercial bulk carrier loaded with British Columbian coal successfully transited the Northwest Passage in September 2013[3]. Perhaps more importantly, ships in larger numbers are already navigating the icy waters of Norway and Russia through the Northeastern Passage, also known as the northern sea route (NSR) — a 3,000 mile passage along Russia's northern coast that connects the Barents and Bering seas. The Russian Federation's Northern Sea Route Administration, which issues permits, provides icebreaker escort and regulates

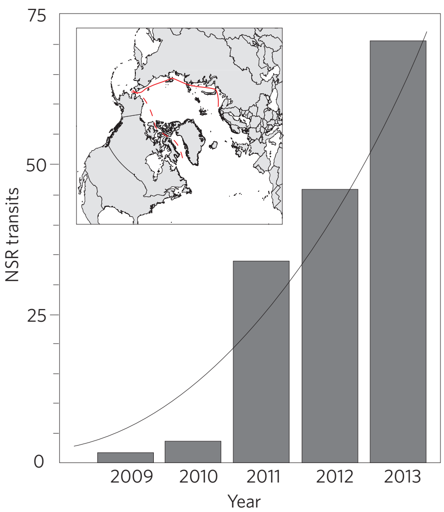

Figure 1 | Annual transits of the Northern Sea Route (NSR) during the period 2009–2013. NSR transits are projected to increase by approximately 20% per year. The solid line is a fit to the data with an equation given by: transits = 1.5448 × (years since 2008)$^{2.4068}$. The goodness-of-fit parameter is R^2 = 0.92251. The inset is a map of the region showing the NSR (solid red line) and the Northwest Passage (dashed red line). Data taken from the Northern Seaway Information Office[5].

commercial ships traversing the NSR, is now open for business[4,5].

Among many potential environmental effects, the continued expansion of Arctic shipping will alter the risk of biological invasions in coastal ecosystems on both regional and global scales. Commercial ships are a dominant mechanism for the introduction of non-native marine species[6,7]. A diverse range of organisms is unintentionally transferred in ballast tanks and on the hulls of ships[8–10]. A major shift in trade-routes will alter the current landscape of marine invasion dynamics, affecting the transfer, establishment and potential consequences of invasions.

There are two categories of commercial Arctic shipping: (1) trans-Arctic voyages, whereby ships use the Arctic as a thoroughfare for interocean passage; (2) destination shipping that moves goods to and from the Arctic (for example, import of oil extraction equipment and export of liquefied natural gas; LNG). Increased opportunity for invasions of the Arctic are an important concern, but trans-Arctic shipping will also change global commerce patterns significantly, connecting world ports and their biota in unprecedented ways. The melting of Arctic sea ice is connecting the North Pacific and North Atlantic oceans for the first time in several million years[11]. Although an ice-free Arctic provides a new interocean corridor for natural dispersal of marine biota across the region, it also represents a new route for long-distance transport of organisms by ships.

Ratification of the maritime delimitation and cooperation in the Barents Sea and the Arctic Ocean treaty, between Norway and Russia in 2011, has settled a decades-long dispute over territorial waters and opened a 175,000 km^2 region of the Barents Sea and Arctic Ocean to oil and gas exploration[12]. This pivotal international agreement paves the way for less politically and legally complicated NSR passage while increasing the opportunity for shipping-related activities in petroleum-rich Arctic waters.

The volume of trans-Arctic shipping traffic is increasing rapidly. Using NSR shipping statistics[5], we plotted annual transits for the 2009–2013 shipping seasons and fitted a growth curve (Fig. 1). In 2013, 71 vessels were reported to have made transit through the NSR, and at least 481 were issued permits to operate inside the NSR[5]. Although the current volume of NSR traffic is still meagre compared with other major shipping routes, it is expanding as quickly, with a projected average annual increase of 20% per year over the next 25 years. At this rate, an estimated 5,600 trans-Arctic transits per year could occur by the year 2040 through the NSR alone. Although this projection provides an initial base function, it will no doubt be strongly affected by three important economic factors: (1) the substantially shorter route between Asia and Europe than afforded by either the Suez or Panama canals; (2) increasing predictability, duration and safety of ice-free conditions; (3) the opportunity for exploration, extraction and exportation of the Arctic's natural resource reserves.

Given expanded exploration, extraction, and exportation of natural resources in the Arctic — ranging from oil, natural gas, rare-earth metals (used extensively in personal electronics and rechargeable batteries) and fish stocks — Arctic shipping is expected to accelerate in the coming years. The Arctic is believed to be home to 13% of global oil supplies and 30% of natural gas; the majority is to be found in Russian territorial lands and waters[13]. Greenland's rare-earth metal reserves are thought sufficient to supply 20–25% of the world's near-term demand[14]. Furthermore, the Arctic is also a growing tourist destination. All of these enterprises will depend on more shipping as well as port and coastal development; activities that disturb and modify the natural environment in ways that can facilitate invasion[15].

Shipping corridors as filters

The opportunity for ship-mediated invasions depends not only on the ports of call but also the particular voyage route or corridor, which affects both the environmental conditions experienced during a voyage and its duration. Most established marine invasions are from bays and estuaries, which are centres of shipping and other transport mechanisms. Just as species composition varies considerably across ports and the ships that visit them, the transit success (survivorship) and fate of organisms varies strongly by specific voyage route, which can act as a filter to limit associated diversity and abundance. In general, survivorship declines with increased voyage duration and with increasing mismatch or fluctuation of the environmental conditions (such as temperature or salinity) encountered during the journey from the source region to the destination.

Commercial ships follow established, dominant intra- and interoceanic trade routes that change over time, sometimes in precipitous fashion. Sudden shifts are perhaps most evident following the creation of interoceanic canals. On completion, the Suez and Panama canals instantly allowed ships to move between oceans, transporting goods among global regions more quickly and economically than ever before. The Suez Canal connects the Egyptian Ports of Said and Tawfiq in the Mediterranean and Red seas, providing passage for vessels moving between the Atlantic and Indian oceans. Before completion of the Suez Canal in 1869, ships sailing between Europe and Asia were forced to sail around South Africa's Cape of Good Hope. The Panama Canal opened in 1914 and connects the Pacific and Caribbean (and greater Atlantic) oceans, minimizing the distance and hazards associated with navigation around South America's Cape Horn.

The Suez and Panama canals rapidly altered the global transportation network and have been dominant corridors over the past century[16]. During the past decade, the average number of annual transits through the Panama Canal has been 12,846 ± 128 (mean ± standard error)[17], roughly 71% that of the Suez Canal: 18,145 ± 534 (ref. 18). Although there was a significant drop in shipping through the Suez during 2008–2009, coincident with the onset of the global economic downturn, shipping through Panama has remained steady, probably because the canal has been operating at its capacity for many years (Fig. 2). These two canals altered the historical patterns of species transfers and are considered responsible for many invasions, due to both ship-mediated transport and natural dispersal[19].

In a similar way, emergence of trans-Arctic shipping via the NSR and the Northwest Passage is expected to cause a rapid shift in global shipping traffic and invasion dynamics over a timescale of years to decades, depending on the rate of sea-ice retreat and market forces. From an invasion perspective, these new shipping routes are significant in several respects. First, Arctic shipping corridors will greatly increase the diversity and abundance of non-native species delivered to high-latitude systems that historically have an extremely low exposure. Second, the environmental conditions and transit times differ from current trans-oceanic shipping routes, which rely heavily on the Panama and Suez canals.

Considering the environmental conditions of these trade routes, both the Suez and Panama canals are located at low latitudes and have relatively warm water — the annual temperature range of the Suez is approximately 17–31 °C (ref. 20) and the Panama Canal has an annual temperature range of 27–32 °C (ref. 21) — but the salinities are quite different. The Suez Canal is largely marine water, with salinities ranging from the high 20s (in practical salinity units) to the low 40s (hypersaline)[20]. In contrast, the Panama Canal traverses a freshwater lake on its interior and is marine at its termini outside the locks. This freshwater exposure is certain to cause osmotic stress and mortality for many marine biofouling organisms clinging to the hulls of ships as they transit the canal, moving between the Atlantic and the Pacific oceans.

Trans-Arctic passages have a very different suite of environmental conditions. Vessels and associated biota (in ballast tanks and on hulls) on these northern corridors experience cold temperatures; a striking contrast to the tropical and subtropical waters of the Panama and Suez Canals (Table 1). In addition, any shift of Atlantic–Pacific traffic from the Panama Canal to trans-Arctic routes removes freshwater exposure, because the latter are entirely marine water routes. Today, most ships sailing between the North Atlantic and the North Pacific transition from cold temperate to warm tropical conditions via the two canals. With the emerging NSR and Northwest Passage options, an increasing proportion of this traffic will be deflected north and experience a transition from cold temperate to polar conditions, without the freshwater exposure associated with the Panama route. It is also noteworthy that the transit time for ships sailing the NSR is far shorter than a tropical route for vessels moving between the North Atlantic and North Pacific. For example, at one end of the spectrum, transit times from Murmansk, Russia to Japan, China and South Korea are approximately 18–20 days, or one-half the time required for a Suez Canal route[5]; such reductions in transit time can affect organism survivorship in and on vessels, which depends on both environmental conditions and voyage duration[22].

Given the strength of the North Atlantic and North Pacific economies and the current trade among them by ships that transit the two canals (Fig. 2), this shift in routes and environmental conditions will also cause a shift in global invasion dynamics. Assuming current practices by ships, we predict two outcomes: (1) a substantial increase in invasions for the Arctic, which has historically received little exposure to such human-mediated transfers; (2) a new and different opportunity for interoceanic translocations of species, especially those unable to withstand the environmental stresses imposed by the Panama and Suez corridors. In short, we predict that Arctic trade routes will result in a large wave of new invasions to cold temperate and polar regions across the North Pacific and North Atlantic oceans, although current research is only now beginning to explore this issue[23,24].

Although there are obvious economic incentives for Arctic shipping, the scope of activities associated with expanded commercial shipping is broad, including the impact from new infrastructure (such as ports, LNG terminals and petroleum drilling rigs), new risks and consequences of oil and chemical spills in Arctic habitats, economic growth and population expansion as well as biological invasions[15]. There is an urgent need for coordinated strategies to focus on the potential for sustainable growth by minimizing environmental impacts of ships and ship-related activities in the Arctic. As invasion ecologists, we have focused primarily on the implications for species transfers in Arctic marine habitats, regions that have been largely isolated from shipping relative to the rest of the globe throughout the Anthropocene.

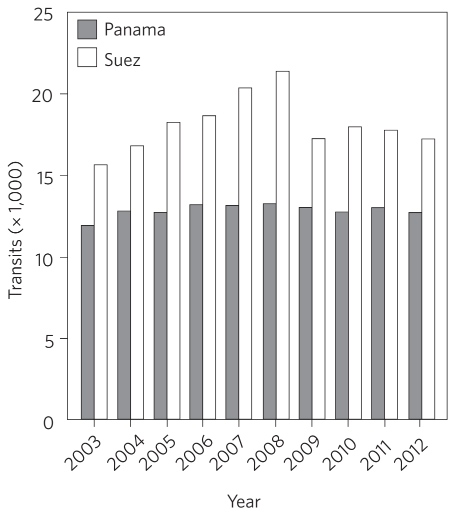

Figure 2 | Annual transits of the Panama and Suez canals during the period 2003–2012. Data taken from Panama Canal and Suez Canal Authorities[17,18].

From shipping alone (that is, ballast water and hull fouling biota), the Arctic is about to undergo extensive and unprecedented biotic inoculations from a vast array of distant Atlantic and Pacific bioregions. However, environmental and ecological impacts on the Arctic go far beyond biological invasions, considering the expanded exploitation of mineral and petroleum reserves[13] as well as living resources such as new commercial fish stocks[25].

The rapid acceleration of Arctic shipping serves as an alarm call to scientists and policy makers concerned with conservation and sustainable use of the marine environment, especially Arctic and cold temperate regions. Emergence of trans-Arctic shipping is a significant game-changer, having the potential to affect a remarkable diversity of coastal marine resources and ecosystem functions. Although there are still critical gaps in our knowledge of specific ecological dynamics and outcomes, there is already sufficient scientific understanding for proactive management and policy in many areas. For invasions, such a strategy includes

Table 1 | Contrasting environmental conditions of three interocean corridors.

	Panama Canal	Suez Canal	Trans-Arctic
Climate	Tropical wet and dry	Hot desert	Polar
Water temperature	Warm	Warm	Cold
Salinity transit sequence (Osmotic stress)	Marine:Fresh:Marine (Severe)	Marine:Poly-hyper:Marine (Moderate)	Marine (None)
Corridor selection	Warm temperature tolerance and low salinity tolerance	Warm temperature tolerance and medium to high salinity tolerance	Cold temperature tolerance

management to prevent (or minimize) species transfers associated with ships and infrastructure (such as drilling rigs and platforms) as well as construction and fisheries activities. ❐

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