Knowledge Mapping for Climate Change and Food- and Waterborne Diseases

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The authors extracted from the PubMed and ScienceDirect bibliographic databases all articles published between 1998 and 2009 that were relevant to climate change and food- and waterborne diseases. Any material within each article that provided information about a relevant pathogen and its relationship with climate and climate change was summarized as a key fact, entered into a relational knowledge base, and tagged with the terminology (predefined terms) used in the field. These terms were organized, quantified, and mapped according to predefined hierarchical categories. For noncholera Vibrio *sp. and* Cryptosporidium *sp., data on climatic and environmental influences (52% and 49% of the total number of key facts, respectively) pertained to specific weather phenomena (as opposed to climate change phenomena) and environmental determinants, whereas information on the potential effects of food-related determinants that might be related to climate or climate change were virtually absent. This proportion was lower for the other pathogens studied (*Campylobacter *sp. 40%,* Salmonella *sp. 27%, Norovirus 25%,* Listeria *sp. 8%), but they all displayed a distinct concentration of information on general food- and water-related determinants or effects, albeit with little detail. Almost no information was available concerning the potential effects of changes in climatic variables on the pathogens evaluated,*

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such as changes in air or water temperature, precipitation, humidity, UV radiation, wind, cloud coverage, sunshine hours, or seasonality. Frequency profiles revealed an abundance of data on weather and food-specific determinants, but also exposed extensive data deficiencies, particularly with regard to the potential effects of climate change on the pathogens evaluated. A reprioritization of public health research is warranted to ensure that funding is dedicated to explicitly studying the effects of changes in climate variables on food- and waterborne diseases.

INTRODUCTION

Climate is changing rapidly due to anthropogenic activity such as extensive fossil fuel combustion and widespread alterations in land use (Intergovernmental Panel on Climate Change, 2007; United Nations Framework Convention on Climate Change, 2007). Global climate change manifests itself through gradual changes, such as increasing air and ocean temperatures and shifting mean annual precipitation or altered seasonality, and through erratic events, such as heavy rainfall and other extreme weather events. These recurrent changes can be ephemeral or persistent, but can bring about a myriad of health threats, many of which can be indirect and elusive, including deaths and hospitalization due to heat waves (Semenza et al., 1999; Semenza et al., 1996), injuries and deaths from flooding (Hajat et al., 2003), the health consequences of hurricanes (Barbeau et al., 2010), and the (re-)emergence of communicable diseases, such as Lyme disease, tick-borne encephalitis, or hantavirus pulmonary syndrome, as well as their shifting distribution (Semenza and Menne, 2009).

Although vector-borne diseases have received considerable attention in discussions about climate change, food- and waterborne diseases are also of interest because their incidence can be directly linked to ambient temperature and precipitation (Semenza and Menne, 2009). Elevated temperatures accelerate the replication cycles of foodborne microorganisms, whereas extended summer seasons may increase the opportunities for deficiencies in food handling. Extreme and erratic rain events can flush parasites that resist chlorination into water treatment and distribution systems, resulting in waterborne outbreaks (Kistemann et al., 2002; Lake et al., 2005; Semenza and Nichols, 2007).

Unfortunately, the multifactorial nature of climate change means that disentangling climatic from socioeconomic, environmental, or behavioral drivers of population health is methodologically intricate. A systematic approach, such as the cataloging and mapping of the existing state of knowledge, can help to identify associations and distinguish significant interactions from confounding ones. We took an ontological approach to comprehensively appraise the links between climate change and food- and waterborne disease. *Ontology* refers to the study of categories of phenomena that exist. It provides a common vocabulary for a domain (e.g., climate change) and defines, with different levels of formality, the meaning of terms and the relationships between them. In artificial intelligence it is used as a specification of conceptualization (Gruber, 1993; Munn and Smith, 2008). We developed an applied ontology that formally represents a set of concepts and vocabulary in the climate change literature to classify related variables and model interactions between them. As such, it provides a conceptual model for analyzing the relationships between climatic variables and food- and waterborne diseases.

Information was extracted from selected articles and organized and structured according to the predefined specifications of the ontology (meta-analysis). Once entered into the ontological knowledge base, the information was searched to quantify and map some of the complex relationships between food- and waterborne pathogens and meteorological variables.

METHODS

Search Strategy and Selection Criteria

Original research articles were retrieved from the PubMed and ScienceDirect bibliographic databases. The search strategies submitted combined the concepts of climate change plus climate variability with food- and waterborne diseases. The search terms were the following: (foodborne [All Fields] OR "food borne" [All Fields] OR "foodborne" [All Fields] OR waterborne [All Fields] OR "water borne" [All Fields] OR "water-borne" [All Fields]) AND ("climate change" [All Fields] OR "climate variability" [All Fields]). Searches were run for the following pathogens and their infections in humans: *Campylobacter* sp., *Cryptosporidium* sp., *Listeria* sp., Norovirus, *Salmonella* sp., and noncholera *Vibrio* sp. These pathogens characterize a cross-section of important food- and waterborne parasites, bacteria, and viruses. Moreover, they represent pathogens from different habitats with a range of susceptibilities to climate variables.

To enlarge and complement the number of records retrieved in the previous searches, further search strategies involved combining the concepts of food poisoning, food microbiology, water, and water microbiology with the
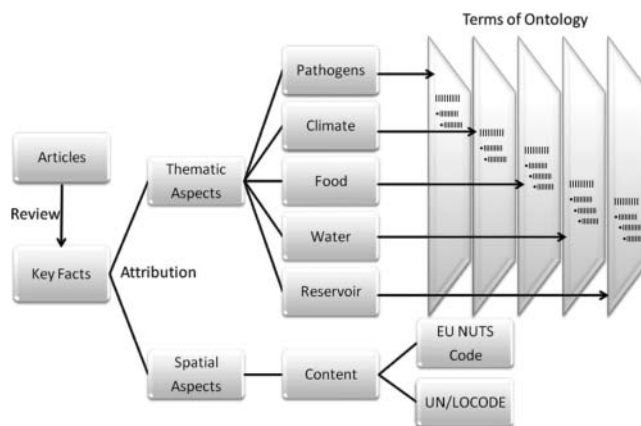
FIGURE 1. Extraction of data (key facts) and mapping of terms (vocabulary) from the peer-reviewed literature (reference sources or articles), according to predefined categories (thematic and spatial aspects) as specified by the climate change ontology for food- and water-borne diseases; 1998–2009. Articles (reference) and sources were identified through bibliographic information systems (PubMed and ScienceDirect) and reviewed by the research team. Information was extracted from articles and summarized into short and concise key facts. Each key fact was assigned to at least one of five principle groups (thematic aspects): pathogens, food, water, climate/environment, and reservoirs, and further tagged with terms from the climate change ontology. A hierarchical organization of the vocabulary (terms), accounted for increasing detail of information (see Table 1). Spatial aspects were also extracted from the articles according to continent, region, and country.

climate change and climate variability concepts (e.g., "*Salmonella* food microbiology" [MeSH] OR "food microbiology" [MeSH] AND "climate" [Major], "climate change" or "climate variability"). Along the same lines, climatic concepts were sometimes included in different search strategies to broaden the number of records retrieved. Key words and MeSH terms (when available) were used in the search strategies for papers in either English or German, published between 1998 and 2009. A particular emphasis was placed on papers from Europe to support a climate change impact assessment of food- and waterborne diseases there (Semenza et al., 2011).

Climate Change Ontology

The results obtained from the literature search were prescreened for their project relevance by reviewing their titles and abstracts (Figure 1). Relevant articles were imported into a separate literature management database (EndNote; Thomson Reuters). All articles relevant to climate change and food- and waterborne diseases were entered into an online, relational knowledge base with the unique ID number as a reference prior to viewing. Each review was tagged automatically with the name of the reviewer and the review

date. Using this online multiuser interface, reviewers examined the vocabulary and terms used for five thematic aspects (pathogens, food, water, climate/environment, and reservoirs) and three spatial aspects (continent, region, and country; Figure 1).

For the pathogenic aspects, subdivisions included bacteria, viruses, and protozoa according to biotaxonomy, an approved microbiological nomenclature. The six pathogens of interest to this study (*Campylobacter* sp., *Cryptosporidium* sp., *Listeria* sp., Norovirus, *Salmonella* sp., and noncholera *Vibrio* sp.) were sorted accordingly. Food-related terms were organized according to the *Codex Alimentarius*, a food ontology of the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO; http://www.codexalimentarius.net). For the remaining thematic aspects (water, climate/environment, and reservoirs) the literature was reviewed for relevant terms. These terms were subjected to rigorous screening by the expert team and integrated into the ontology after expert assessment. The ontology was updated if necessary throughout the process with new ontology terms. Rare cases of discordance between reviewers (<1%) were resolved by consensus. This formal mapping of terms constitutes the ontological approach.

Ontological Knowledge Base

Reviewers read articles retrieved from the online, relational knowledge base and short and concise key facts were extracted from these articles. Key facts were defined as any facts within an article that provided information about a relevant pathogen and its relationship to climate and climate change. They were in the form of short summaries, recorded as brief sentences or citations from the article and captured pertinent information from the study. To facilitate queries within the database, each key fact was assigned to at least one or more of the five principle groups (thematic aspects): pathogens, food, water, climate/environment, and reservoirs (Table 1; Appendix A). The key facts, consisting of short sentences, were tagged with the ontological terms (as described previously) for data mining and data mapping purposes.

Articles could contribute key facts to as many predefined thematic aspects as relevant, as key facts represented any information about pathogen behavior in the environment or the disease itself. Thus, any one publication could provide multiple key facts (and ontological terms) with no upper limit per source. An article about *Campylobacter* sp. and air temperature, for example, would have been assigned the thematic aspects of pathogens and climate/environment.

The article per se was categorized according to the body of evidence, quality, and directness of inference made in the study. The body of evidence

TABLE 1. Hierarchical organization of vocabulary used in climate change ontology for food- and waterborne diseases; 1998–2009

1: food
- meat and meat products
  - fresh meat
    - beef || pork || veal
  - processed meat
    - nonheated processed || cured nonheated || cured + dried || fermented nonheat treated || heat treated || frozen
  - fresh poultry
  - processed poultry
    - nonheated processed || cured nonheated || cured and dried || fermented nonheat treated || heat treated || frozen
  - fresh game
  - processed game
    - nonheated processed || cured nonheated || cured and dried || fermented nonheat treated || heat treated || frozen
- fish and fish products
  - fresh fish
  - processed fish and fish products
    - frozen || frozen battered || frozen minced || cooked or fried || smoked, dried, fermented, salted || semipreserved || fully preserved
- molluscs, crustaceans, echinoids.
  - fresh
  - processed
    - frozen || frozen battered || frozen minced || cooked or fried || smoked, dried, fermented, salted || semipreserved || fully preserved
- eggs and egg products
  - fresh eggs
  - preserved eggs
  - egg-based deserts
  - egg products
    - liquid || frozen || dried and/or heat coagulated
- sauces, salads, spices
  - sauces and similar products || salads || mayonnaise || herbs || vinegars || mustards || soups and broth || yeast and like products || soybean products fermented/nonfermented
- fruit
  - fresh fruit
    - untreated || surface treated || peeled or cut
  - processed fruits
    - frozen || dried || canned || cooked || jams, jellies, marmalades || candied || fermented
  - vegetables
  - fresh vegetables
    - untreated || surface treated || peeled or shredded
  - processed vegetables
    - frozen || dried || canned || cooked or fried || in vinegar (pickled) || vegetable spread || fermented
- confectionery
  - cocoa products
    - cocoa mixes || cocoa spreads || chocolate products || chocolate substitutes
  - candies and nougats
    - candies || nougat || marzipan
  - decorations
- cereals
  - whole, ground, or flaked || grains, including rice || breakfast cereals || pre-cooked cereal products || soybean products

- bakery items
  - ○ breads and rolls ‖ crackers ‖ fine bakery items
- sweeteners
  - ○ honey ‖ sugar ‖ syrups
- dairy products
  - ○ milk and dairy-based drinks
    - ▪ fresh pasteurized ‖ fresh nonpasteurized ‖ sterilized ‖ skimmed milk ‖ buttermilk ‖ yogurt drinks ‖ flavored milk
  - ○ whey
    - ▪ plain whey ‖ whey drinks
  - ○ renneted milk products
    - ▪ fluid fermented milk ‖ plain yogurt ‖ curdled milk
  - ○ condensed milk products
    - ▪ sweetened condensed milk ‖ evaporated milk ‖ beverage whiteners ‖ dehydrated milk
  - ○ cream and similar products
    - ▪ **pasteurized cream ‖ clotted cream**
  - ○ milk powder
  - ○ cheese
    - ▪ raw milk cheese ‖ unripened cheese ‖ ripened cheese
  - ○ dairy-based deserts
    - ▪ pudding ‖ fruit yogurt ‖ ice cream ‖ iced milk ‖ jellied milk
  - ○ butter, milk fat, ghee

2: water
- usage
  - ○ tap water
    - ▪ groundwater ‖ surface water ‖ home-carbonated
  - ○ bottled water
    - ▪ carbonated ‖ still (not carbonated)
  - ○ recreational water
    - ▪ sea water ‖ swimming pool/spa ‖ river ‖ reservoir, lake, pond
  - ○ food production
    - ▪ groundwater ‖ surface water
  - ○ irrigation
    - ▪ groundwater ‖ surface water
- water body
  - ○ groundwater ‖ surface water ‖ sea ‖ rain ‖ glacier ‖ wastewater
- contamination
  - ○ wastewater ‖ feces ‖
  - ○ diffuse ‖ storm water sewer overflow

3: pathogens
- bacteria
  - ○ *Campylobacter* spp.
  - ○ *Salmonella* spp.
  - ○ *Listeria* spp.
  - ○ *Vibrio* spp. noncholera
- viruses
  - ○ Norovirus
  - ○ Enterovirus (reserve)
- parasites
  - ○ *Cryptosporidium* spp.

4: climate/environment
- air temperature
  - ○ change in: T ‖ T max ‖ T min ‖ T avg.
- water temperature
  - ○ change in: increasing T ‖ decreasing T ‖ T max ‖ T min ‖ T avg.

TABLE 1. Hierarchical organization of vocabulary used in climate change ontology for food- and waterborne diseases; 1998–2009 *(Continued)*

- precipitation
  - change in: precipitation ‖ pattern
- (extreme) event
  - flood ‖ drought ‖ storm ‖ heavy rainfall event ‖ snow melt
- relative humidity
  - increase ‖ decrease
- sunshine hours
  - increase ‖ decrease
- UV light
  - change in: intensity ‖ exposure
- wind
  - change in: wind strength ‖ direction
- cloud coverage
  - change in cloud coverage
- seasonality
  - rainy season ‖ dry season ‖ summer ‖ winter ‖ change in seasonal pattern
- time
  - time between: tmax air to event ‖ tmax water to event ‖ time precipitation air to event ‖ extreme.weather event to outbreak
- water salinity

5: reservoirs
- fowl
  - poultry
    - chicken ‖ domestic. ducks ‖ domestic. geese ‖ turkey
  - wild birds
    - wild ducks ‖ wild geese
- ruminants
  - cattle ‖ calves ‖ sheep
- fish
  - salmon ‖ trout
- molluscs
  - clams ‖ oysters
- reptiles
  - crocodiles
  - snakes
- rodents
  - mice, rats ‖ rabbits, beaver
- pig
- pets
  - cats ‖ dogs ‖ reptiles

Note. Ontological terms extracted from the peer-reviewed literature and organized according to four levels of hierarchy. The resolution and extent of detail of ontological terms is enhanced by each increasing level (e.g., level 4) in the hierarchy. Hierarchies are indented with bullets, if available; "‖" states alternatives within the same subcategory.

was grouped as meta-analyses, systematic reviews, randomized controlled trials, nonrandomized intervention studies, cohort, case-control studies, cross-sectional (surveys), ecological studies, case studies, in vivo experiments, in vitro experiments, molecular evidence, expert opinion, or other. These categories were not used to rank the quality of articles per se but drawn on during the interpretation of key facts.

The quality of each study was rated based on the GRADE approach (Grade Working Group, 2004; Guyatt et al., 2008). Expert reviewers were trained in the GRADE quality criteria prior to grading. Uncertainty about the directness or quality of evidence was resolved during expert meetings and the rare occasions of discordance between reviewers were resolved by consensus. The quality of evidence was influenced by the study limitations (design and size), the methodology applied, the consistency of results, the directness of evidence, precision, and reporting bias.

Articles were graded according to predefined categories: high, moderate, low, and very low quality. The criteria guiding the grading of quality were the following:

- High: Further research is very unlikely to change confidence in the estimate of the effect (e.g., experimental data in a controlled laboratory setting indicating pathogen die-off after UV-exposure).
- Moderate: Further research is likely to have significant impact on confidence in the effect estimate and may affect point estimates (e.g., single-case studies).
- Low: Further research is very likely to have an important impact on confidence in the effect estimate and is likely to change that estimate (e.g., case studies in a complex environmental setting estimating long-term effects).
- Very low: Any estimate of effect is very uncertain (e.g., opinions).

Moreover, data extracted from articles were assessed according to the degree of causal inference. An article was rated as direct to signify strong causality (e.g., a controlled experimental setting) and the practical applicability of its content to the objectives of this current analysis. Articles rated moderate indicated strong circumstantial evidence (e.g., epidemiological evidence), but data taken from these articles required cross-referencing with other studies and careful interpretation before use. Articles rated indirect did not permit causal inference and their content was only used as background information. Information in a specific article that was not pertinent to climate change and food- and waterborne diseases was not tagged with key facts or ontology terms. Entire articles not related to the subject matter were marked as not relevant; thus, every article was tagged with at least one comment.

The ontological knowledge base facilitated the search for specific ontological terms tagged to the key facts and connections between meteorological and environmental determinants and pathogens through advanced data-mining techniques, by searching for specific topics to identify information, key facts, ontology terms, quality of data, and articles for a literature review (Semenza et al., 2011).

Data Analysis

The consistency and scalable organization of information facilitated the refined retrieval of relevant information through customized queries. Summary statistics of ontology terms by pathogen or environmental determinant were generated. Relationships and interactions between factors could be analyzed according to these thematic aspects and ontological terms. To visualize the results, semantic network maps and 3D maps were created with Flash and GIS applications, as described subsequently.

Semantic network maps were created using the open source Flare library (Heer et al., 2005; UC Berkeley Visualization Lab, 2010) together with Adobe Flex (Kazoun and Lott, 2008). The source code of the Flare Dependency Graph was modified and joined with the result of an adjusted SQL request to provide data to the visual interface.

To produce the 3D maps of ontological terms in the knowledge base, a SQL request was processed in the database, which calculated the number of ontological terms that combined single thematic aspects for a selected pathogen. This computation provides the pathogen specific number of ontological terms for every thematic aspect. The results were converted into a spreadsheet where the hierarchy position was computed into polar coordinates. The result was imported into a Geographic Information System (ArcGIS, ESRI, Redlands, CA), which enabled the creation of a Triangulated Irregular Network (TIN) from the points calculated. The coordinate system chosen was the North Pole Azimuthal Equidistant, which provided a view parallel to the earth's axis. The results were then imported into 3D GIS software (ArcScene, ESRI; Kennedy, 2009) for visualization, which allowed for the adjustment of vertical exaggeration and the selection of a viewpoint.

In addition to thematic aspects, spatial aspects (e.g., outbreak location) were selected by ascribing ontological terms to one of the predefined regions, where geographical information was available in the articles. Spatial information was based on (EU-)NUTS (Regulation EC No 1059, 2003) and the United Nations Code for Trade and Transport Locations (UN/LOCODE code; Figure 1). By linking ontological terms with spatial aspects the information was mapped using a Web GIS tool on Google Maps.

RESULTS

Climate Change Ontology

We created an ontology of the climate change vocabulary for food- and waterborne diseases. The literature search identified 722 articles, which were examined for the terms and vocabulary used. Based on this review and other existing ontologies, 275 terms were chosen to populate the ontology (Table 1). The terms were selected based on the vocabulary used in the

literature and organized according to five thematic aspects (pathogens, food, water, climate/environment, and reservoirs), which were further subdivided according to a hierarchy of four levels with increasing resolution of detail. For example, an article could have provided terms under the thematic aspect food according to four hierarchical categories, which were, from lowest to highest resolution: food, meat and meat products, fresh meat, and beef. This hierarchical organization is shown in Table 1 with a bulleted list of terms used. However, not all articles provided information to the highest level of detail and thus not all articles contributed to the higher resolution categories.

Ontological Knowledge Base

Information was extracted from the selected articles in the form of key facts (short concise data) and transformed into machine-readable data to enable knowledge-driven data mining (Figure 1). In total, 1,642 key facts (comprising approximately 50,000 words) were extracted from these articles; 1,625 had thematic aspects and 1,068 had spatial aspects. Key facts assigned to the terms of the ontology were allocated to the hierarchical order with four levels (bulleted list in Table 1), generating a total of 6,341 data points in the ontological knowledge base. Articles were examined carefully to determine the levels of detail provided for pathogens, food, water, climate/environment, and reservoirs, which were then assigned to the hierarchical level in Table 1. The articles were also graded according to data quality, study design, data source, and causal inference, as previously described.

Share of Climate Data Compared With Total

We summarized the number of ontological terms in the knowledge base for each pathogen by thematic aspect (food, water, climate/environment, and reservoirs) to expose potential discrepancies in frequencies. In the context of our search terms (as described previously), we computed the proportion of ontological terms from the thematic aspect climate/environment relative to all other ontological terms (Figure 2). The majority of ontological terms for noncholera *Vibrio* sp. (52% of the 124 total ontological terms), and 49% of ontological terms for *Cryptosporidium* sp. (of 190 total ontological terms) pertained to climate/environment. Thus, most of the information on these two pathogens related to climatic or environmental determinants. This proportion was smaller for the other pathogens examined: *Campylobacter* sp. 40% (of 453 ontological terms), *Salmonella* sp. 27% (of 369 ontological terms), Norovirus infection 25% (of 206 ontological terms), and *Listeria* sp. 8% (of 119 ontological terms). These results call attention to a discrepancy in research findings by subject matter: for *Listeria* sp. climatic and environmental aspects are a minor area of published research, in contrast to *Vibrio* sp. and *Cryptosporidium* sp. Because *climate* and *climate change* were required
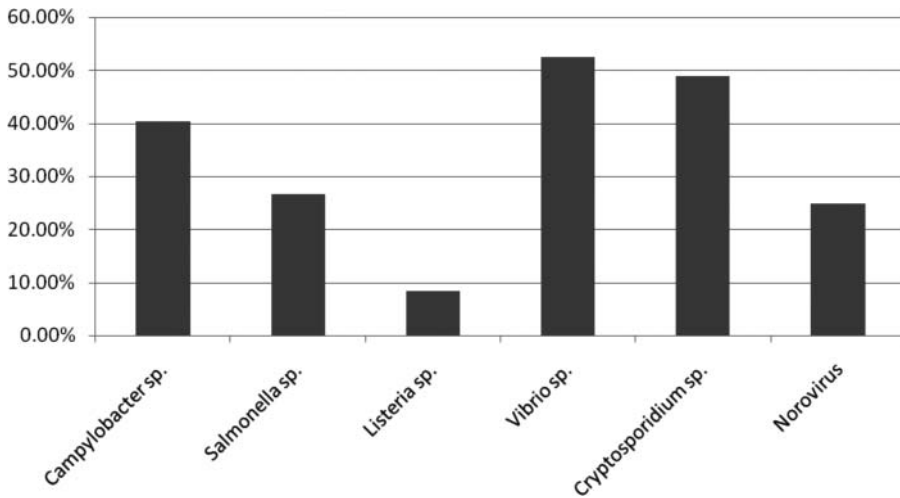
FIGURE 2. Proportion of climate/environmental terms relative to all terms by pathogen, extracted from the ontological knowledgebase for climate change and food- and waterborne diseases, 1998–2009. Absolute number of climate/environmental terms was divided by all terms available in the ontological knowledgebase for each pathogen. Total number of terms for *Campylobacter*: 453, *Salmonella*: 369, *Cryptosporidium*: 190, *Listeria*: 119, Norovirus: 206, and noncholera *Vibrio*: 124.

terms of our search, this discrepancy would have been even more distorted without these search requirements.

Span of Research Topics Covered

The breadth and detail of ontological terms in the ontological knowledge base was examined. Frequency distributions of ontological terms by thematic aspects and pathogens are presented in Table 2. The records of topics covered represent the breadth of research data. The table quantifies the information on determinants presently available in the ontological knowledge base; zero indicates a lack of published data (no data) in the papers reviewed. In general, the distribution of ontological terms is wider for the more prevalent pathogens with a higher diversity of different ontological terms. All pathogens have ontological terms for the more general categories (e.g., food, water, seasonality), but the ontological knowledge base can pinpoint which pathogen has ontological terms for which specific exposure pathway: specific food items (e.g., eggs, dairy, fruits) or specific water features (e.g., ground, sea, bottled water, tap water). For example, extreme climatic events (e.g., heavy precipitation, floods, storms, droughts) were associated with selected pathogens only. Hence, Table 2 is an overview of the span of research topics covered by ontological terms. However, this summary overview does not differentiate whether an association is positive (e.g., relative risk >1,

TABLE 2. The number of ontological terms by pathogen, for four thematic aspects: climate/environment, water, food, and reservoir; extracted from the ontological knowledge base for climate change and food- and waterborne diseases, 1998–2009

Key facts	Campylo bacter	Salmonella	Listeria	Vibrio	Crypto sporidium	Norovirus
Climate/environment						
Seasonality	59	29	3	15	33	46
Changes in seasonal pattern	1	0	0	0	3	0
Air or water temperature	110	56	0	57	15	4
Average and extreme temperature	14	24	0	10	3	0
Changes in temperature	16	32	0	33	6	0
Precipitation and pattern	19	4	0	2	21	0
Changes in precipitation	0	0	0	0	11	0
Heavy rainfall event	14	0	0	8	27	2
Flood	2	2	0	1	4	2
Storm	0	0	0	8	0	0
Drought	1	0	0	0	3	0
UV light	15	6	3	1	9	0
Changes in UV radiation exposure or intensity	0	0	2	0	2	0
Salinity	0	0	0	22	1	0
Changes in wind	0	1	0	0	0	0
Change in cloud coverage	0	0	0	0	0	0
Water						
Surface water	106	11	3	4	31	15
Ground water	14	2	0	0	4	5
Rain	3	0	0	0	0	0
Seawater	15	8	0	44	5	3
Tap and bottled water	41	3	0	0	21	26
Recreational water	10	3	0	3	8	1
Water for food production and irrigation	0	8	0	3	1	0
Water contamination	43	14	5	0	38	33
Wastewater	9	8	3	0	6	11
Food						
Meat and meat products	51	50	23	1	2	1
Fish and shellfisch	12	10	13	54	1	12
Eggs and egg products	1	36	1	1	0	0
Dairy products	17	16	17	0	3	0
Fruits and vegetables	11	41	7	0	4	6
Cereals and bakery items	2	12	4	2	0	2
Sauces, salads, spices, confectionery, sweeteners	2	11	3	0	2	1
Reservoirs						
Fowl	27	10	0	0	1	0
Ruminants	11	0	0	0	3	0
Pigs	0	4	0	0	1	0
Pets	3	10	0	0	1	0
Fish	0	0	0	2	1	0
Mollusk	0	3	0	14	0	5
Reptiles	0	0	0	0	1	0
Rodents	0	0	0	0	1	0
Not specified	6	2	0	1	9	0

Note. Not mutually exclusive categories.

increased risk) or negative (e.g., relative risk <1, protective), which is discussed in Semenza et al. (2011). The list merely quantifies the ontological terms presently in the literature.

Data Resolution

In the climate and water categories, *Campylobacter* sp. contributed the largest number of ontological terms relative to the other pathogens (Table 2). In the food category, however, *Salmonella* sp. had the most entries. Comparatively, these two pathogens contribute to the largest burden of foodborne disease in Europe (European Centre for Disease Prevention and Control, 2009). In contrast, less ontological terms could be derived for *Listeria* sp., a relatively rare disease in Europe. The quantity of data differs also across the four hierarchical levels of the ontology. The stacked list of bulleted vocabulary used is shown in Table 1, where level 4 provides the highest level of detail in the hierarchy. We analyzed the degree of detail (and resolution) by computing all ontological terms for each of the four levels of the hierarchy. The number of ontological terms by hierarchical order is summarized in Appendix B, stratified by pathogen and thematic aspects. Food aspects displayed a wider distribution across the hierarchies than did the other thematic aspects. Thus, extensive detailed information was available for food items, but only minimal detail for climate/environment aspects, which were limited to only three levels (Table 1). This lack of differentiation of the terms for climate/environment may be a reflection of limitations in the field.

Lack of Data on Change

The frequency profile of ontological terms is illustrated in 3D maps for each pathogen (Figure 3). Four thematic aspects (reservoir, food, water, climate/environment) were arranged in a circle. Ontological terms with little detail were plotted in the centre whereas ontological terms with more detail were mapped toward the periphery, according to the ontological hierarchy. The numbers of ontological terms were summed to a peak, with the elevation being proportional to the frequency. Ontological terms for *Campylobacter* sp. peaked with specific water (tap and surface water) and weather data (temperature); the low level resolution of food/water aspects was visible through a crater-like data ring. For *Salmonella* sp., the crater-like data ring for food/water ontological terms was even more pronounced and differentiated with a number of higher detail data peaks, which were available for food aspects (pork, fresh poultry, fresh eggs, and vegetables) as well.
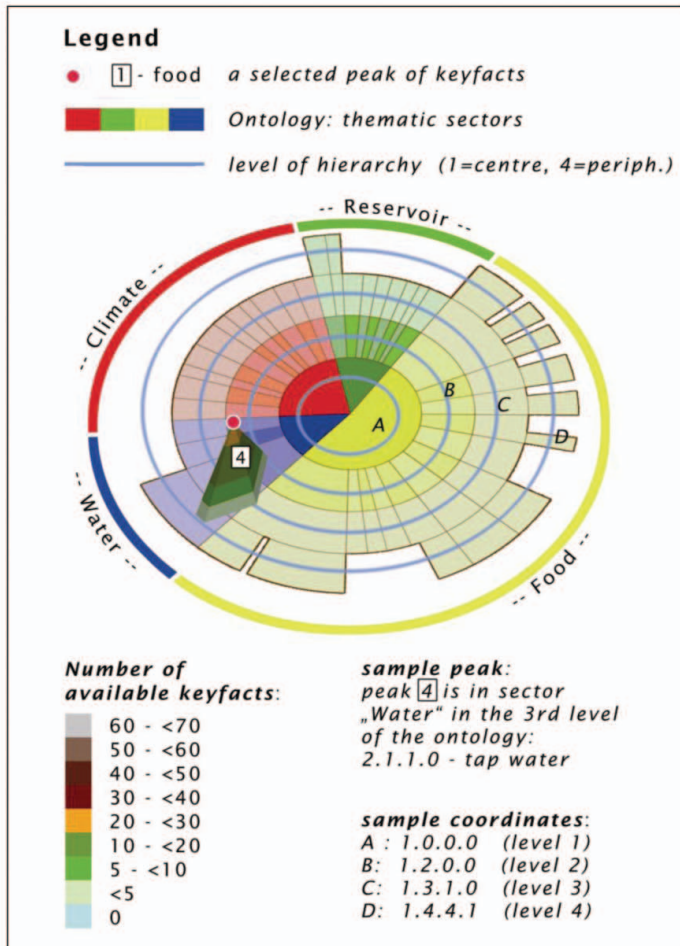
Ontological terms for *Cryptosporidium* sp. are slanted toward climate/environment and water aspects, with no data peaks for the food or reservoir aspects, in stark contrast with the data availability for *Listeria* sp. with virtually all the data peaks in the food aspects. Norovirus has a similar data distribution
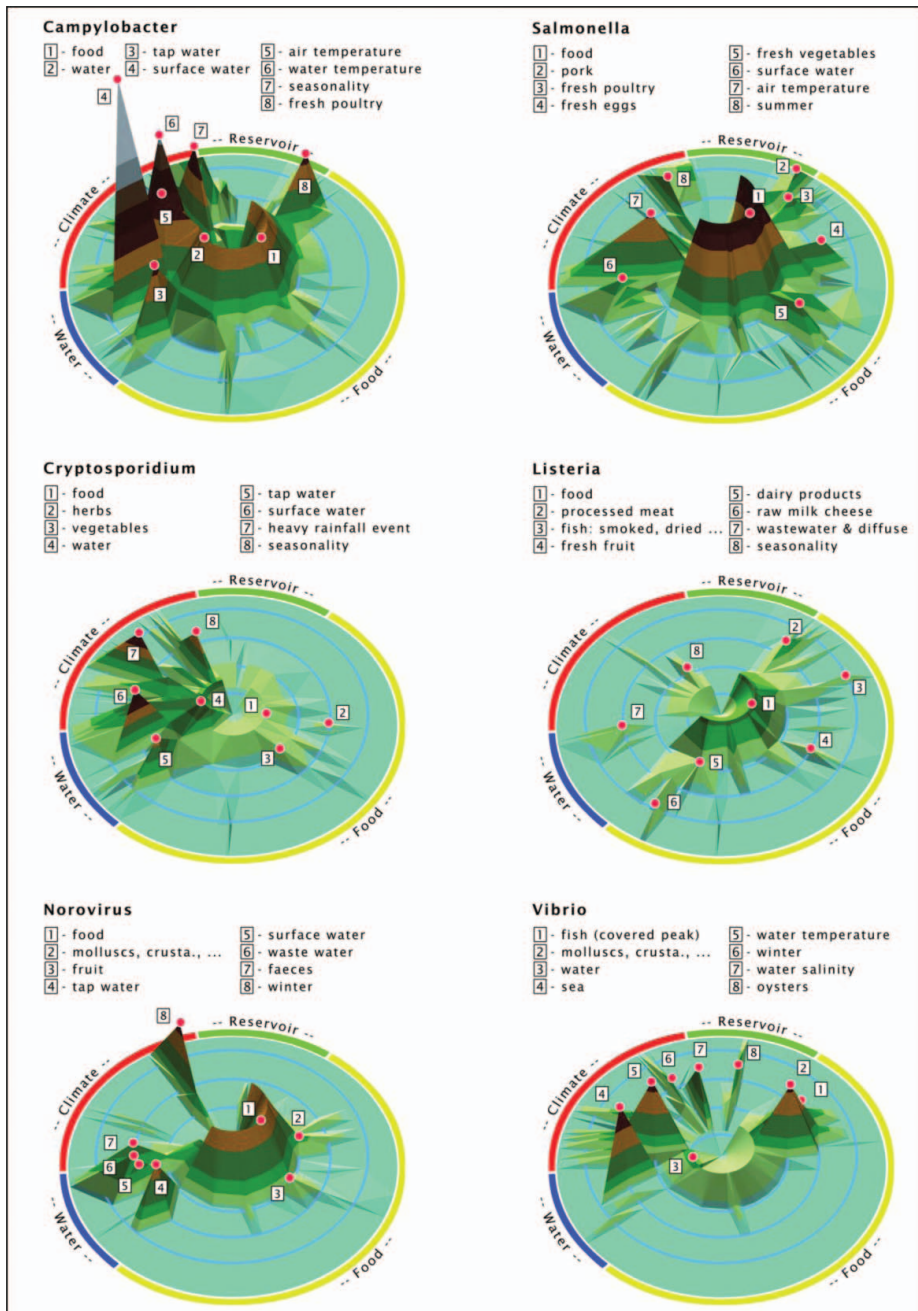
FIGURE 3. Frequency profile of terms mapped to information from the peer-reviewed literature. Terms are organized by thematic aspect and pathogen, visualized through elevation. Thematic aspects (reservoir, food, water, and climate/environment) are arranged in a circle. Elevation of a peak corresponds to the number of terms. The "crater-like" data ring in the centre represents general food and water terms with little detail. Peripheral data peaks represent terms with more detail. Terms extracted from the ontological knowledgebase for food- and water-borne diseases, 1998–2009 (Color figure available online).

Note: These terms correspond to the terminology used in the literature and are mapped by thematic aspect for each pathogen, according to the four level hierarchy of the climate change ontology (Table 1). Each term is assigned a (polar) coordinate. All terms which combine a selected pathogen with a thematic aspect add up to a peak at its coordinate. Terms towards the pole represent little detail (low resolution information) while key facts at the periphery correspond to high level detail. For example, four levels of hierarchy from low to high: food (little detail); meat and meat products; fresh meat; beef (high level detail). Elevation of a peak is shaded in different colours to reflect the number of key facts. For details see the legend below.

FIGURE 3. Continued (Color figure available online).

to *Listeria* sp., although a few data peaks are present outside the food domain. The 3D rendering of the *Vibrio* sp. ontological terms is similar to the representation of the *Cryptosporidium* sp. ontological terms, with a skewed distribution toward climate/environment and water aspects.

Figure 3 reveals a wealth of low-resolution data for food and water determinants for most of the pathogens studied, which are visible through a crater-like data ring. No such crater-like data ring is detectable for climate/ environment. Prominent weather events or food items stand out occasionally, represented by high elevation data peaks toward the periphery of the 3D map. However, no significant key fact signal, capturing a change of meteorological variables, is noticeable in Figure 3, with the exception of heavy rainfall events for *Cryptosporidium* sp. This observation is also supported by relatively few ontological terms in Table 2 for changes in temperature, precipitation. Thus, measurements of a changing climate and the implications of this for these pathogens are sparse.

Web of Connections

Ties between thematic aspects themselves were also visualized. Links were plotted on semantic network maps by drawing strings representing relationships (Figure 4). Specific thematic aspects (e.g., temperature) are heavily networked with other thematic aspects from other categories (e.g., food, water, seasonality). For example, the semantic network map for precipitation connects rain to certain food items (e.g., fresh and processed poultry, fish and fish products, mollusks, crustaceans) whereas air temperature is linked to others (e.g., fresh eggs, salads, fruit, vegetables). Conversely, food items can be activated and connected to pathogens and other determinants; for example, seafood was linked to all six pathogens and a number of other important environmental determinants (Appendix C). The pathogens implicated can then be identified and investigated. These semantic maps show the multivariate nature of climate change and the complex interactions with environmental determinants.

Origin of Data

The geographical location of key facts was plotted on European maps to identify where the study was conducted, where the outbreak occurred, or

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FIGURE 4. Semantic network maps by thematic attributes; derived from the ontological knowledgebase for climate change and food- and waterborne diseases, 1998–2009. Maps to be read clockwise: thematic aspects are arranged concentrically and color-coded (food = yellow; water = blue; pathogens = pink; climate/environment = green). Precipitation and air temperature terms on the left of the circle are colored blue and initiate connections with other terms, represented with red stings linking to red terms. Gray strings in the background represent the network of all connections not activated in this view. The list of 275 terms in the ontology has been reduced for this map to approximately 140 terms due to space restrictions. The fourth level of the hierarchy was deleted for this map but the link was retained by moving it to its ancestor items at the third level (Color figure available online).

climate – air temperature

climate – precipitation
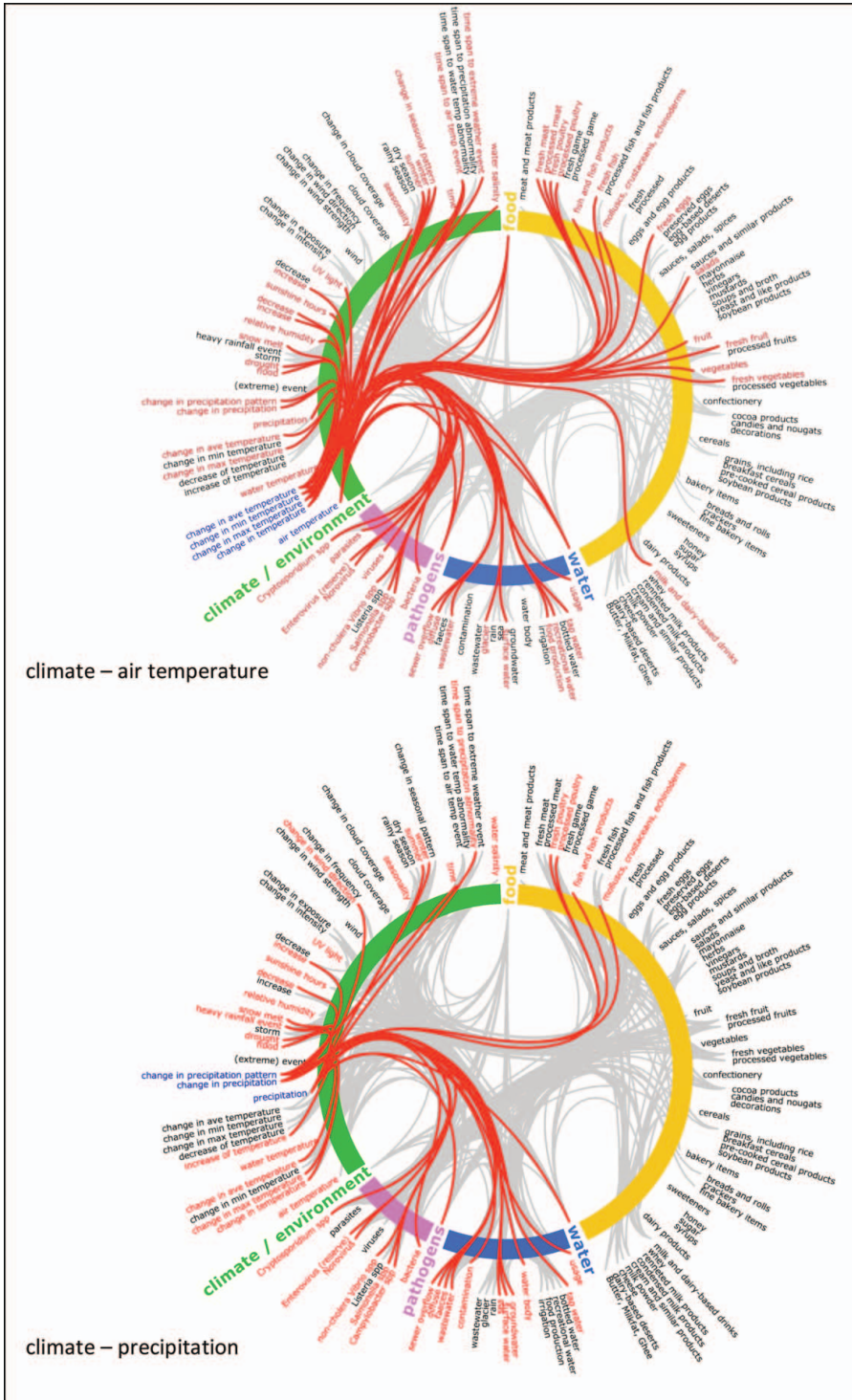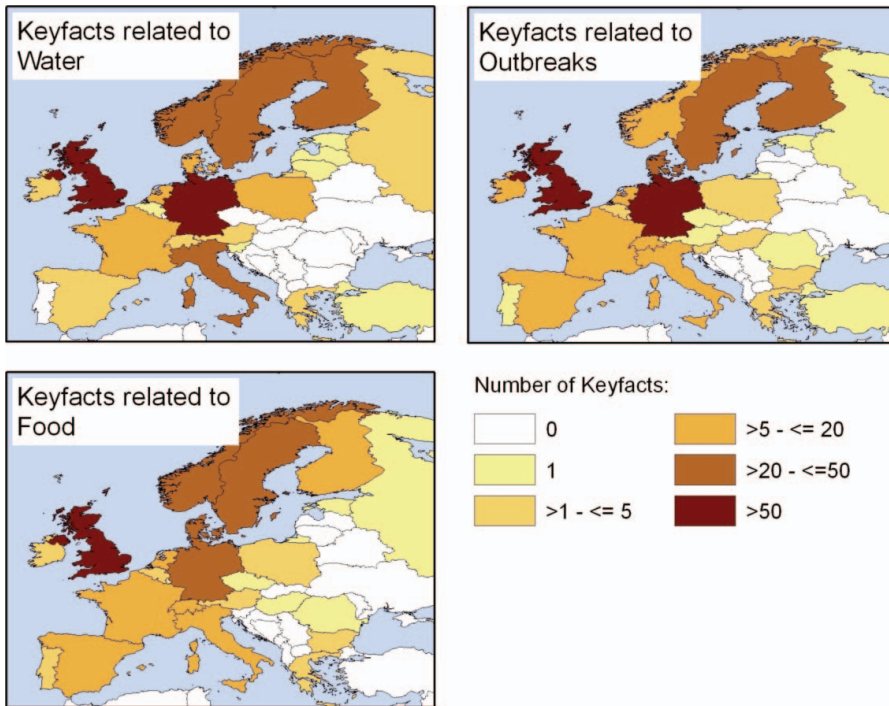
FIGURE 5. Location of data (key facts) extracted from the peer-reviewed literature, related to thematic aspects of water, food, and outbreaks by country; ontological knowledge base for climate change and food- and waterborne diseases, 1998–2009. The data (key facts) pertain to the location or origin of the extracted information, and specifically, where the study was conducted, where the outbreak occurred, or where the laboratory research was carried out. Country- and region-specific information can be extracted for further analysis (Color figure available online).

where the laboratory research was carried out (Figure 5). Presently, the ontological knowledge base holds 4,809 spatial attributes from the NUTS and LOCODE lists, which corresponds to 95% of all the available aspects (275 from the ontology and 4,809 from the spatial list).

A preponderance of key facts was identified in Northern Europe, with less data from Southern and Eastern/Central Europe. The number of articles by country followed a very similar geospatial pattern to the key facts, with the majority of articles covering *Salmonella* sp., *Campylobacter* sp., and Norovirus; fewer articles were available for *Cryptosporidium* sp., *Listeria* sp., and noncholera *Vibrio* sp. with the same geographical gradient (data not shown).

DISCUSSION

In this paper we present an attempt to systematically scrutinize, catalog, quantify and map the present state of knowledge of recent research on climate change and food- and waterborne diseases. One limitation of the study is publication bias (Petitti, 1994). The articles retrieved were not evenly distributed throughout Europe, with north-south and west-east gradients (Figure 5). This observation is in part due to the selective retrieval of published reports in English or German from bibliographic databases, but also due to underreporting. The lack of information on climate change and these food- and waterborne diseases could pose a risk to public health, particularly at times of financial recession, which could lead to the underfunding of surveillance and control programs. National vulnerability, impact, and adaptation assessments can counteract these weaknesses by prioritizing adaptation options (European Centre for Disease Prevention and Control, 2010). This ontological knowledge base can be searched by public health practitioners conducting such an assessment to retrieve disease specific information pertaining to their country or region (Figure 5). The information can then be evaluated and subjected to a decision algorithm for adaptation options. Conversely, data mining of the ontological knowledge base may also bring to light data gaps for vulnerability, impact and adaptation assessments (European Centre for Disease Prevention and Control, 2010) that may trigger investigations or research studies into the health impacts of climate change. The subsequent discussion by environmental determinates illustrates the discrepancy between the state of climate change knowledge in other disciplines (e.g., meteorology, ecology, biology) compared with the health field.

The field of public health lags behind other disciplines in terms of climate change research. A Web of Science search of climate change publications across all disciplines (articles, proceedings papers, reviews, editorials, or news items for the period of 1990–2010) retrieved almost 9,000 publications in environmental science and over 6,000 publications in each of the disciplines of meteorology, ecology, or the geosciences. However, only 498 climate change publications were retrieved for public, environmental, or occupational health combined, a large part of which were reviews and not primary research papers. This deficiency in health information is in part a consequence of insufficient allocation of climate change funds to the health field when compared with other disciplines (Ebi et al., 2009). Presently, no rigorous quantitative models exist that project the health impacts of climate change, with the exception of heat waves and air pollution, which are relatively recent compared with the models available in agriculture that have been used for projections for more than a decade (Kristie L. Ebi,), personal communication, September 2009). The subsequent discussion juxtaposes meteorological, ecological, or biological climate change observations to the ontological terms available in the health field. This quantitative comparison of

data points is complemented by a separate review of the contents of key facts (comprising approximately 50,000 words in the ontological knowledge base) to evaluate the actual evidence base (Semenza et al., 2011).

Temperature Determinants

Temperature can directly impact multiplication and more indirectly the transmission pathways of food- and waterborne diseases. The global average temperature is now 0.8°C higher than in preindustrial times (1850–1919), whereas in Europe this average is 1.4°C higher (Climate Research Unit, 2006). Conservative projections foresee a continuing upward trend in global mean air temperatures, increasing by 1.8–4.0°C this century, whereas other models suggest an increase range of 1.1–6.4°C (Intergovernmental Panel on Climate Change, 2007). The last decade was the warmest on record, with 1998 and 2005 reaching historic levels, which could potentially impact incidence rates. *Campylobacter* sp. and *Salmonella* sp. recorded the highest number of ontological terms for air temperature (32 and 41 ontological terms, respectively) compared with the other pathogens studied (Figure 3).

For water temperature, *Campylobacter* sp. (64 ontological terms) and noncholera *Vibrio* sp. (35 ontological terms) had the most key fact entries (Figure 3), presumably fresh and coastal water, respectively. Even though ocean temperatures have not increased as rapidly due to the large effective heat capacity of water, as well as heat loss from evaporation, the temperature of coastal waters has risen. The northern hemisphere has warmed faster than the southern hemisphere due to its greater land mass (World Meteorological Organization, 2008).

Temperature Change

The most dramatic increase in temperature has been recorded in the Arctic region of Europe, where temperatures have risen by 3°C over the last 90 years (Arctic Climate Impact Assessment, 2004). Northern Europe is a geographical area with a high projected temperature increase according to climate change scenarios (Schröter et al., 2005). This projected change is particularly pronounced for winter rather than summer months, with increases in the range of 8–10°C forecast by the year 2080 (Arctic Climate Impact Assessment, 2004). Southern and Central Europe are projected to experience temperature increases during the summer months of up to 6°C (Giannakopoulos et al., 2005; Räisänen et al., 2004).

These well-documented projected increases in temperature stand in contrast to the paucity of data on the potential effects of temperature changes on the pathogens evaluated in the ontological knowledge base. Explicitly ontological terms relevant to the potential effects of temperature changes were the following: changes in air temperature (38 ontological terms) as well as changes in maximum (10), minimum (2), and average temperature (19), the

majority of which were for *Salmonella* sp. Human health impact assessments rely on exposure response relationships but the lack of data linking global warming with increased incidence rates makes projections very difficult.

Seasonality

Another aspect of global environmental change is altered seasonal patterns. Season is an important epidemiologic determinant of most food- and water-borne pathogens, with the possible exception of *Listeria* sp. (Semenza et al., 2011). In Europe, the spring and summer seasons have warmed the most, whereas autumn has warmed less. Observational studies in several areas of Europe have documented a lengthening of the time period between the last spring frost and the first autumn frost over recent decades (Root et al., 2003; Tait and Zheng, 2003). The arrival of spring and summer phenological events, such as the onset of the pollen season, the first flowering date of plant species, or the onset of animal breeding, advanced on average by 2.5 days per decade between 1971 and 2000 (Menzel et al., 2006). Strong seasonality signals (in ontological terms) were recorded for all pathogens studied with the exception of *Listeria* sp. Specifically, the seasonality of winter and summer was covered by the most ontological terms (Figure 3). However, changes in seasonal patterns were only captured by a handful of ontological terms. These seasonal shifts, which are well documented in other disciplines, leave the question open as to whether the seasonality of food- and waterborne pathogens has changed as well.

Extreme Events

Gradual changes in climate are often overshadowed by extreme weather events. Although individual events are difficult to link to climate change as a statistical phenomenon, the intensity, duration, and frequency of such extreme events can be. The ontological knowledge base lists 99 ontological terms relevant to the potential effects of extreme events on the pathogens evaluated: 51 address heavy rainfall events, 11 address floods, 4 address droughts, 6 address snowmelts, and 8 address storms (Table 2). Climate models predict that heat waves will become more common, hotter, and longer lasting (Beniston, 2004). Over the last decade, Europe has recorded historically high ambient temperatures during the summer months, notably during the 2003 heat wave, but no key fact identified heat waves explicitly in the ontological knowledge base. Similarly, droughts have increased in frequency and intensity while the number of cold spells has fallen (Giorgi et al., 2004), but they were not covered by many ontological terms. Storms are associated with strong winds capable of causing substantial land surface damage and temporary increases in sea level. Storminess over the last century has varied considerably in Europe, but in more recent years has been relatively calm (Matulla et al., 2007). Climate projections indicate an overall

decrease in the number of storms, although the strengths of the strongest storms may augment.

Precipitation Determinants

Precipitation is an important environmental determinant for these pathogens, as it affects transport, survival, and transmission; *Campylobacter* sp. and *Cryptosporidium* sp. had the most ontological terms for precipitation in the ontological knowledge base (Table 2). Mean annual precipitation in Europe has changed significantly; during the 20th century, Northern Europe has witnessed a 10–40% increase, whereas Southern Europe has seen a 20% decrease in mean annual precipitation (Giorgi et al., 2004). Trends in precipitation are significantly more difficult to predict than temperature, as is reflected in the wide range of projections for different climate models and scenarios (Schröter et al., 2005). Thus, projecting health impacts is particularly challenging.

In general, precipitation in Northern Europe is projected to increase, particularly during the winter months, but decrease further in the south, mainly during the summer months. Of the pathogens studied, only *Cryptosporidium* sp. provided information relevant to the potential effects of changing precipitation patterns. Reductions in precipitation in parts of Mediterranean Europe may also be accompanied by longer periods of drought (Palutikof and Holt, 2004), but virtually no ontological terms were recorded for the potential effects of drought on the pathogens evaluated.

Extreme precipitation events are also projected to increase in Western and Northern Europe, but not in the south (Good et al., 2006; Palmer and Räisänen, 2002). The ontological knowledge base captured ontological terms for heavy rain events for *Cryptosporidium* sp. (27 terms), *Campylobacter sp.* (14 terms), and noncholera *Vibrio* sp. (8 terms; Table 2).

CONCLUSION

Analysis of ontological terms in this ontological knowledge base generated a number of pertinent observations. Data on the potential effects of climate change on food- and waterborne diseases are practically nonexistent, and ontological terms capturing the potential effects of changes in meteorological conditions are sparse. The climate/environment information presently available is characterized by data peaks representing the potential effects of individual meteorological variables or weather events on pathogens rather than climate change specifically. Thus, without data on a changing climate for exposure response relationships, projections are difficult. The data generated by the scientific community fails to be relevant and cannot be applied to model and forecast global environmental change (McMichael, 1993).

Information on several potentially important factors impacting transmission is still missing (Table 2). Although it is obvious that not all pathogens are equally climate-related, very little information on the potential impact of climatic factors on disease transmission of *Listeria* sp. is available to date, and it is a pathogen with increasing disease incidence. Moreover, the semantic networks between pathogens and thematic aspects illustrate a rich web of interconnections, but methods to analyze these interactions are inadequate.

In summary, we aimed to quantify available data on the potential influence of climatic and environmental variables on six food- and waterborne diseases. The ontological approach assured a comprehensive appraisal of the field, which can be extended in a consistent and methodical way in the future. Differences were evident among the pathogens examined with regard to patterns of connectivity, the proportions of climatic and environmental determinants relative to all ontological terms, and the overall extent of information concerning the potential effects of these determinants. Most striking, however, is the shortage of specific climate change data for projecting health impacts. It is particularly difficult to assess the impact of climate change because it acts as a risk multiplier and thus exacerbates existing vulnerabilities (Semenza and Giesecke, 2008). Moreover, it has been proposed that climate change will result in a shifting distribution of communicable diseases in Europe, but the multifactorial nature of this phenomenon makes it difficult to predict (Semenza and Menne, 2009). Nevertheless, information available in this ontological knowledge base can be utilized to initiate adaptation efforts. Vulnerability, impact, and adaptation assessments can help strengthen the public health infrastructure and provide cobenefits for society at large.

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APPENDIX A
Number of Terms in Ontological Knowledge Base

Number of terms are listed that are attributed to a thematic aspect. Subcategories are not summarized in the leading headlines

Hierarchy	Ontology name	Number of Terms
1.0.0.0	***food***	***114***
1.1.0.0	**meat and meat products**	**16**
1.1.1.0	fresh meat	14
1.1.1.1	beef	7
1.1.1.2	pork	18
1.1.1.3	veal	1
1.1.2.0	processed meat	22
1.1.2.1	nonheated processed	3
1.1.2.2	cured nonheated	0
1.1.2.3	cured and dried	1
1.1.2.4	fermented nonheat treated	2
1.1.2.5	heat treated	7
1.1.2.6	frozen	1
1.1.3.0	fresh poultry	56
1.1.4.0	processed poultry	20
1.1.4.1	nonheated processed	0
1.1.4.3	cured nonheated	0
1.1.4.4	cured and dried	0
1.1.4.5	fermented nonheat treated	0
1.1.4.6	heat treated	3
1.1.4.7	frozen	0
1.1.5.0	fresh game	0
1.1.6.0	processed game	0
1.1.6.1	nonheated processed	0
1.1.6.2	cured nonheated	0
1.1.6.3	cured and dried	0
1.1.6.4	fermented nonheat treated	0
1.1.6.5	heat treated	0
1.1.6.6	frozen	0
1.2.0.0	**fish and fish products**	**34**
1.2.1.0	fresh fish	12
1.2.2.0	processed fish and fish products	2
1.2.2.1	frozen	0
1.2.2.2	frozen battered	0
1.2.2.3	frozen minced	1
1.2.2.4	cooked or fried	0
1.2.2.5	smoked, dried, fermented, salted	5
1.2.2.6	semipreserved	0
1.2.2.7	fully preserved	0
1.3.0.0	**molluscs, crustaceans, echinoderms**	**64**
1.3.1.0	fresh	14
1.3.2.0	processed	0
1.3.2.1	frozen	0
1.3.2.2	frozen battered	0
1.3.2.3	frozen minced	0
1.3.2.4	cooked or fried	1

(Continued on next page)

Hierarchy	Ontology name	Number of Terms
1.3.2.5	smoked, dried, fermented, salted	0
1.3.2.6	semipreserved	0
1.3.2.7	fully preserved	0
1.4.0.0	**eggs and egg products**	**21**
1.4.1.0	fresh eggs	18
1.4.2.0	preserved eggs	0
1.4.3.0	egg-based deserts	2
1.4.4.0	egg products	1
1.4.4.1	liquid	0
1.4.4.2	frozen	0
1.4.4.3	dried and/or heat coagulated	1
1.5.0.0	**sauces, salads, spices**	**7**
1.5.1.0	sauces and similar products	3
1.5.2.0	salads	10
1.5.3.0	mayonnaise	0
1.5.4.0	herbs	4
1.5.5.0	vinegars	0
1.5.6.0	mustards	0
1.5.7.0	soups and broth	0
1.5.8.0	yeast and like products	0
1.5.9.0	soybean products fermented/nonfermented	0
1.6.0.0	**fruit**	**21**
1.6.1.0	fresh fruit	19
1.6.1.1	untreated	5
1.6.1.2	surface treated	1
1.6.1.3	peeled or cut	0
1.6.2.0	processed fruits	0
1.6.2.1	frozen	0
1.6.2.2	dried	0
1.6.2.3	canned	0
1.6.2.4	cooked	0
1.6.2.5	jams, jellies, marmalades	0
1.6.2.6	candied	0
1.6.2.7	fermented	1
1.7.0.0	**vegetables**	**25**
1.7.1.0	fresh vegetables	22
1.7.1.1	untreated	5
1.7.1.2	surface treated	2
1.7.1.3	peeled or shredded	0
1.7.2.0	processed vegetables	0
1.7.2.1	frozen	0
1.7.2.2	dried	1
1.7.2.3	canned	0
1.7.2.4	cooked or fried	1
1.7.2.5	in vinegar (pickled)	0
1.7.2.6	vegetable spread	0
1.7.2.7	fermented	0
1.8.0.0	**confectionery**	**0**
1.8.1.0	cocoa products	1
1.8.1.1	cocoa mixes	0
1.8.1.2	cocoa spreads	0
1.8.1.3	chocolate products	4
1.8.1.4	chocolate substitutes	0
1.8.2.0	candies and nougats	0

Hierarchy	Ontology name	Number of Terms
1.8.2.1	candies	0
1.8.2.2	nougat	0
1.8.2.3	marzipan	0
1.8.3.0	decorations	0
1.9.0.0	**cereals**	**0**
1.9.1.0	whole, ground, or flaked grains, including rice	5
1.9.2.0	breakfast cereals	0
1.9.3.0	pre-cooked cereal products	0
1.9.4.0	soybean products	0
1.10.0.0	**bakery items**	**19**
1.10.1.0	breads and rolls	1
1.10.2.0	crackers	0
1.10.3.0	fine bakery items	2
1.11.0.0	**sweeteners**	**0**
1.11.1.0	honey	0
1.11.2.0	sugar	0
1.11.3.0	syrups	0
1.12.0.0	**dairy products**	**22**
1.12.1.0	milk and dairy-based drinks	6
1.12.1.1	fresh pasteurized	1
1.12.1.2	fresh nonpasteurized	11
1.12.1.3	sterilized	0
1.12.1.4	skimmed milk	1
1.12.1.5	buttermilk	0
1.12.1.6	yogurt drinks	0
1.12.1.7	flavored milk	0
1.12.2.0	whey	0
1.12.2.1	plain whey	0
1.12.2.2	whey drinks	0
1.12.3.0	renneted milk products	0
1.12.3.1	fluid fermented milk	0
1.12.3.2	plain yogurt	0
1.12.3.3	curdled milk	0
1.12.4.0	condensed milk products	0
1.12.4.1	sweetened condensed milk	0
1.12.4.2	evaporated milk	0
1.12.4.3	beverage whiteners	0
1.12.4.4	dehydrated milk	0
1.12.5.0	cream and similar products	1
1.12.5.1	pasteurized cream	0
1.12.5.2	clotted cream	0
1.12.6.0	milk powder	2
1.12.7.0	cheese	8
1.12.7.1	raw milk cheese	6
1.12.7.2	unripened cheese	0
1.12.7.3	ripened cheese	4
1.12.8.0	dairy-based deserts	0
1.12.8.1	pudding	0
1.12.8.2	fruit yogurt	0
1.12.8.3	ice cream	0
1.12.8.4	iced milk	0
1.12.8.5	jellied milk	0
1.12.9.0	Butter, Milkfat, Ghee	4

Hierarchy	Ontology name	Number of Terms
2.0.0.0	***water***	***73***
2.1.0.0	**usage**	**18**
2.1.1.0	tap water	110
2.1.1.1	groundwater	6
2.1.1.2	surface water	7
2.1.1.3	carbonized at home	0
2.1.2.0	bottled water	4
2.1.2.1	carbonated	0
2.1.2.2	still (not carbonated)	0
2.1.3.0	recreational water	16
2.1.3.1	sea water	8
2.1.3.2	swimming pool/spa	7
2.1.3.3	river	2
2.1.3.4	reservoir, lake, pond	2
2.1.4.0	food production	5
2.1.4.1	ground water	0
2.1.4.2	surface water	0
2.1.5.0	irrigation	9
2.1.5.1	groundwater	0
2.1.5.2	surface water	1
2.2.0.0	**water body**	**16**
2.2.1.0	groundwater	46
2.2.2.0	surface water	188
2.2.3.0	sea	87
2.2.4.0	rain	3
2.2.5.0	glacier	2
2.2.6.0	wastewater	19
2.3.0.0	**contamination**	**50**
2.3.1.0	wastewater	47
2.3.2.0	feces	51
2.3.3.0	diffuse	21
2.3.4.0	stormwater/sewer overflow	28
3.0.0.0	***pathogens***	***136***
3.1.0.0	**bacteria**	**50**
3.1.1.0	Campylobacter spp.	453
3.1.2.0	Salmonella spp.	369
3.1.3.0	Listeria spp.	119
3.1.4.0	Vibrio spp. noncholera	124
3.2.0.0	**viruses**	**31**
3.2.1.0	Norovirus	206
3.2.2.0	Enterovirus (reserve)	16
3.3.0.0	**parasites**	**10**
3.3.1.0	Cryptosporidium spp.	190
4.0.0.0	***climate/environment***	***35***
4.1.0.0	**air temperature**	**82**
4.1.1.0	change in temperature (increase/decrease)	47
4.1.2.0	change in maximum temperature (increase/decrease)	11
4.1.3.0	change in minimum temperature (increase/decrease)	2
4.1.4.0	change in average temperature (increase/decrease)	22

Hierarchy	Ontology name	Number of Terms
4.2.0.0	**water temperature**	**126**
4.2.1.0	change in increase of temperature (increase/decrease)	11
4.2.2.0	change in decrease of temperature (increase/decrease)	1
4.2.3.0	change in maximum temperature (increase/decrease)	8
4.2.4.0	change in minimum temperature (increase/decrease)	0
4.2.5.0	change in average temperature (increase/decrease)	7
4.3.0.0	**precipitation**	**59**
4.3.1.0	change in precipitation (increase/decrease)	13
4.3.3.0	change in precipitation pattern	9
4.4.0.0	**(extreme) event**	**4**
4.4.1.0	flood	19
4.4.2.0	drought	5
4.4.3.0	storm	8
4.4.4.0	heavy rainfall event	74
4.4.5.0	snow melt	6
4.5.0.0	**relative humidity**	**25**
4.5.1.0	increase	2
4.5.2.0	decrease	2
4.6.0.0	**sunshine hours**	**12**
4.6.1.0	increase	4
4.6.2.0	decrease	0
4.7.0.0	**UV light**	**37**
4.7.1.0	change in intensity	2
4.7.2.0	change in exposure	4
4.8.0.0	**wind**	**3**
4.8.1.0	change in wind strength	0
4.8.2.0	change in wind direction	1
4.8.3.0	change in frequency	0
4.9.0.0	**cloud coverage**	**1**
4.9.1.0	change in cloud coverage	0
4.10.0.0	**seasonality**	**104**
4.10.1.0	rainy season	5
4.10.2.0	dry season	2
4.10.3.0	summer	55
4.10.4.0	winter	56
4.10.5.0	change in seasonal pattern	10
4.11.0.0	**time**	**4**
4.11.1.0	time span between air temperature abnormality and event	6
4.11.2.0	time span between water temperature abnormality and event	0
4.11.3.0	time span between precipitation abnormality and event	1
4.11.4.0	time span between extreme weather event and pathogen/disease/outbreak	2
4.12.0.0	water salinity	28

Hierarchy	Ontology name	Number of Terms
5.0.0.0	***reservoirs***	***16***
5.1.0.0	**fowl**	**2**
5.1.1.0	poultry	11
5.1.1.1	chicken	20
5.1.1.2	domesticated ducks	0
5.1.1.3	domesticated geese	0
5.1.1.4	turkey	1
5.1.2.0	wild birds	4
5.1.2.1	wild ducks	0
5.1.2.2	wild geese	0
5.2.0.0	**ruminants**	**1**
5.2.1.0	cattle	9
5.2.2.0	calve	1
5.2.3.0	sheep	3
5.3.0.0	**fish**	**4**
5.3.1.0	salmon	0
5.3.2.0	trout	0
5.4.0.0	**mollusks**	**9**
5.4.1.0	clams	0
5.4.2.0	oysters	10
5.5.0.0	**reptiles**	**1**
5.5.1.0	crocodiles	0
5.5.2.0	snakes	0
5.6.0.0	**rodents**	**1**
5.6.1.0	mice, rats	0
5.6.2.0	rabbits, beaver, …	0
5.7.0.0	**pig**	**5**
5.8.0.0	**pets**	**2**
5.8.1.0	cats	3
5.8.2.0	dogs	3
5.8.3.0	reptiles	9

APPENDIX B
Number of Terms, by Hierarchical Level (x*.0.0.0)

The number of terms was stratified by pathogen and thematic aspect and extracted from the ontological knowledgebase for climate change and food- and waterborne diseases, 1998–2009

Numbers of terms for each hierarchical level represent the level of detail available for a certain thematic aspect

	Campylo-bacter	Salmonella	Listeria	Vibrio	Crypto-sporidium	Norovirus
Climate/ environment						
4.0.0.0	5	5	3	1	6	1
4.x.0.0	136	56	5	44	44	14
4.x.x.0	45	48	2	31	48	37
Food						
1.0.0.0	27	40	11	5	3	27
1.x.0.0	29	42	15	40	6	13
1.x.x.0	47	77	28	16	4	7
1.x.x.x	14	40	20	1	1	1
Water						
2.0.0.0	27	6	1	6	14	9
2.x.0.0.	29	2	0	0	20	6
2.x.x.0	171	35	5	45	66	54
2.x.x.x	8	0	0	3	9	1
Reservoirs						
5.0.0.0	10	3	0	0	1	0
5.x.0.0	1	8	0	7	1	5
5.x.x.0	25	10	0	10	1	0
5.x.x.x	12	9	0	0	0	0

Note. x* = any subcategory >0. Four levels of hierarchy are presented except for climate/environment although only three hierarchical levels were available. The distribution for food terms is rather wide but much narrower for water and reservoir terms, which peak at hierarchy level 3.