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Review

A review of quantitative microbial risk assessment and consumer process models for *Campylobacter* in broiler chickens

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ABSTRACT

Quantitative Microbial Risk Assessment (QMRA) is an important tool for the characterization of complex exposure pathways that contribute to adverse human and animal health outcomes. *Campylobacter* spp. contamination in the broiler chicken farm-to-fork continuum has been the focus of many QMRA models, including those, such as Consumer Process Models (CPMs), which focus solely on *Campylobacter* survival as a function of consumer behaviour during meal preparation. Previous review articles published by other researchers provided summaries and comparisons of existing *Campylobacter*/broiler chicken QMRAs and CPMs. We performed a comprehensive literature search to identify QMRAs and CPMs available after 2011, or otherwise omitted from previous reviews, to further describe what has become an extensive body of work. A total of five new QMRAs and six CPMs were identified, and are presented herein. Together, collections such as these represent important resources for the development of novel risk assessments, identification and prioritization of persistent knowledge gaps, and recognition of advancements with respect to modelling *Campylobacter* contamination throughout the broiler chicken farm-to-fork continuum.

1. Introduction

Campylobacter spp. is a leading cause of acute gastroenteritis worldwide (Kaakoush et al., 2015). In Canada, the incidence of foodborne campylobacteriosis exceeds that of both *Escherichia coli* and *Salmonella* spp. infections by an order of magnitude (Thomas et al., 2013). The average annual incidence rate of campylobacteriosis in Canada from all sources between 2003 and 2013 was 29 cases per 100,000 persons, though higher regional incidence rates have been reported (Kaakoush et al., 2015; Public Health Agency of Canada, 2016). Human exposure routes include contact with domestic or wild animals, insects, or livestock, and consumption of contaminated water or various foods including raw milk. Human campylobacteriosis is most commonly associated with the consumption of poultry–specifically fresh, portioned or whole broiler meat products (Humphrey et al., 2007; Kaakoush et al., 2015; Vellinga & Van Loock, 2002). While campylobacteriosis is generally non-severe and self-limiting, resulting sequelae, such as Guillain–Barré Syndrome, can be debilitating and life threatening (Israeli et al., 2012).

Over the past decade, a number of independent researchers and national food safety agencies have described the dissemination and survival of *Campylobacter* along the broiler chicken farm-to-fork continuum using a Quantitative Microbial Risk Assessment (QMRA) model and/or Consumer Process Model (CPM). Stochastic risk models are robust tools that can be used for evidence-informed decision-making, and are uniquely suited to manage a wide breadth of data and interpret the variability and uncertainty inherent of microbial populations (Vose, 2008). Despite the relatively consistent nature of broiler meat production in the western world, modelling approaches, assumptions, and techniques have varied significantly with the availability of data, intended use and function of the model, and scale of assessment.

In 2009, Nauta et al. performed an extensive review and comparison of six national-level *Campylobacter* risk assessment models. Later, Nauta and Christensen (2011) reviewed the performance of eight *Campylobacter* CPMs, several of which were included in the models previously reviewed. Together, these publications provided a comprehensive overview of the state of modelling efforts with respect to *Campylobacter* in the broiler chicken farm-to-fork continuum at that time.

At present, there is interest in the creation of a Canadian *Campylobacter* risk assessment model, owing to both the significant burden of disease of *Campylobacter* in Canada, and the absence of a recent comprehensive model constructed in the context of a North American production environment. To this end, we performed a literature search to identify QMRAs and CPMs available

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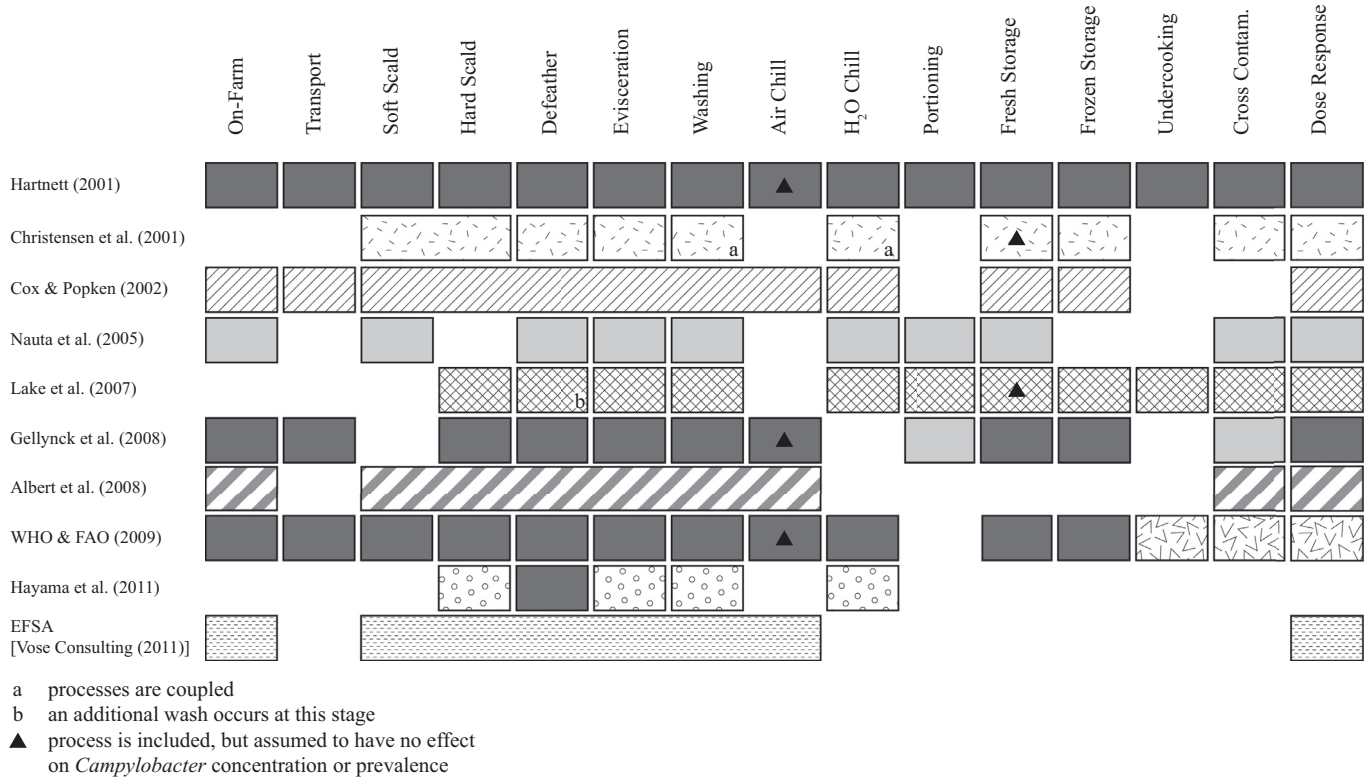

Fig. 1. A comparison and source identification of quantitative microbial risk assessment model components. Boxes indicate inclusion of the component in the respective model. The models are ordered chronologically; where patterns are conserved, components were replicated from prior models. The absence of a box indicates omission of that component. Where boxes extend through multiple stages, those stages were treated as a single component in the model.

after the completion of, or otherwise not included in, the Nauta et al. (2009) and Nauta and Christensen (2011) reviews. Moreover, we present these new QMRAs and CPMs in the context of the existing identified literature to provide insight into persistent knowledge gaps and trends in modelling assumptions, considerations, and techniques.

2. Methods

A search strategy was developed to identify published literature describing one or more facets of modelling *Campylobacter* in the broiler production system. The searches were intentionally broad, reflecting the scope of a farm-to-fork model. The literature search was conducted in two phases, each consisting of two searches. The initial phase was conducted in May 2013, and included a primary search using Scopus and a secondary search using PubMed. No date limitations were imposed on the primary search, to capture any articles omitted from the Nauta et al. (2009) and Nauta and Christensen (2011) reviews. The secondary search was limited to those articles published between 2009-May 2013 (inclusively), as it was expected that the relevant literature published prior to 2009 was captured through both the primary search, and in the earlier QMRA and CPM reviews (Nauta et al., 2009; Nauta & Christensen, 2011). It is important to note that our differentiation between QMRAs and CPMs is artificial; QMRA is an umbrella term that encompasses the modelling of both processing and consumer handling of products. We simply stratify models as QMRAs (spanning from broiler rearing, through all stages of processing and retail) and CPMs (spanning from retail through human consumption) for clarity and consistency.

The primary search algorithm consisted of the following terms: (quantitative OR microbial OR risk OR cost OR burden) AND (assessment OR model* OR analysis OR characterization) AND (campy* OR illness) AND (chicken OR broiler OR poultry). The search terms were limited to article title, abstract, and keyword fields. No restrictions were placed on document type or subject area. The secondary search consisted of the above terms, in addition to the MeSH (Medical Subject Headings) terms: ("Risk Assessment"[Mesh]) AND ("*Campylobacter*"[Mesh]). No field restrictions were included while using PubMed. Where captured articles formally described, presented, or summarized portions of otherwise unpublished models, the original models were subsequently acquired from the grey literature. No attempt was made to catalogue or translate literature available in languages other than English.

The second phase of the search was conducted from January through February of 2016. For the second phase of the search, the primary and secondary searches were replicated with a limited date range of 2013-February 2016 using the same parameters as the first phase. The search algorithm was optimized through elimination of the search term "illness", and validated against the initial search through successful retrieval of previously identified literature.

3. Results

The Nauta et al. (2009) and Nauta and Christensen (2011) reviews included six QMRAs [one of which we classified here as a CPM (Section 3.1.5)] and eight CPMs, respectively. Of the eight CPMs, four were components of the previously identified QMRAs, and four were stand-alone models. An additional five QMRAs and six CPMs were captured in our literature searches. Given that several of these captured QMRAs are iterations of prior models, we have included a short summary and publication history of all QMRAs for comparison. The stages of processing considered in each QMRA are also indicated (Fig. 1). A subset of these QMRAs can be compared using the Interactive Catalogue on Risk Assessment