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Review

Impacts of climate change on the microbial safety of pre-harvest leafy green vegetables as indicated by *Escherichia coli* O157 and *Salmonella* spp.

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ABSTRACT

The likelihood of leafy green vegetable (LGV) contamination and the associated pathogen growth and survival are strongly related to climatic conditions. Particularly temperature increase and precipitation pattern changes have a close relationship not only with the fate and transport of enteric bacteria, but also with their growth and survival. Using all relevant literature, this study reviews and synthesises major impacts of climate change (temperature increases and precipitation pattern changes) on contamination sources (manure, soil, surface water, sewage and wildlife) and pathways of foodborne pathogens (focussing on *Escherichia coli* O157 and *Salmonella* spp.) on pre-harvested LGVs. Whether climate change increases their prevalence depends not only on the resulting local balance of the positive and negative impacts but also on the selected regional climate change scenarios. However, the contamination risks are likely to increase. This review shows the need for quantitative modelling approaches with scenario analyses and additional laboratory experiments. This study gives an extensive overview of the impacts of climate change on the contamination of pre-harvested LGVs and shows that climate change should not be ignored in food safety management and research.

Contents

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1. Introduction

Fresh fruit and vegetables are increasingly recognized as an important source of foodborne disease outbreaks in many parts of the world (Beatty et al., 2004; Cummings et al., 2001; FAO/WHO, 2008; Gajraj et al., 2012; Hanning et al., 2009; Moretti et al., 2010; Sivapalasingam et al., 2004; Wendel et al., 2009). The risks of foodborne disease caused by fresh produce are illustrated by multiple outbreaks with high numbers of illnesses in several regions of the world, such as in Europe (Friesema et al., 2008; Horby et al., 2003; Nygård et al., 2008; Söderström et al., 2005; Söderström et al., 2008; Takkinen et al., 2005), the United States (Ackers et al., 1998; Mody et al., 2011; Wendel et al., 2009), Japan (Michino et al., 1999) and Australia (FAO/WHO, 2008). Every year approximately 76 million people in the US become ill from foodborne disease and over 12% of these disease cases are linked to fresh produce (Klonsky, 2006). The European percentage is similar (Miraglia et al., 2009). One of the causes of foodborne disease is contamination of fresh produce by foodborne pathogens originating from manure, soil, sewage, surface water or wildlife.

Leafy green vegetables (LGVs) are identified as the fresh produce commodity group of highest concern from a microbiological safety perspective (FAO/WHO, 2008), because they are often grown in the open field and vulnerable to contamination from contaminated manure used as fertilizer, soil, water used for irrigation, and contact with (faeces of) wildlife (FAO/WHO, 2008). Moreover, they are grown and consumed raw and in large volumes. Bacteria, such as *Salmonella* spp. and pathogenic *Escherichia coli* strains, are the main pathogens causing foodborne disease through LGVs (Friesema et al., 2008; Gajraj et al., 2012; Söderström et al., 2008; Takkinen et al., 2005).

The incidence in foodborne disease is generally correlated with climate conditions (Jacxsens et al., 2010; Miraglia et al., 2009; Tirado et al., 2010). Roughly one-third (population attributable fraction) of salmonellosis cases in England, Wales, Poland, the Netherlands, the Czech Republic, and Switzerland can be linked to higher temperatures (Semenza and Menne, 2009). In Australia, the rate of salmonellosis also increases with decreasing latitude and consequently with increasing average yearly temperatures (Hall et al., 2002). These seasonal salmonellosis patterns were statistically correlated with the mean monthly temperature of the previous month (D'Souza et al., 2004). Similarly, in the Australian subtropical and tropical regions, temperature and rainfall were positively associated with the number of salmonellosis cases (Zhang et al., 2010). The mechanisms underlying the observed seasonality in foodborne disease are not fully understood, but they are likely a complex interplay of different factors. These include human behaviour and consumption patterns (Van Staveren et al., 1986; Ziegler et al., 1987), pathogen prevalence in the animal reservoir and pathogen environmental survival patterns. The risk of foodborne disease is directly related to the prevalence of bacteria on LGVs. The likelihood of LGV contamination and the associated pathogen concentrations are strongly related to environmental conditions. Though uncertain, the observed seasonality and climate relationships should thus not be ignored; they may result in higher risks.

Changes in temperature, distribution of precipitation (including more extreme events, such as floods and droughts), UV and moisture content are already observed worldwide (Meehl et al., 2007). Temperature has increased since the start of observations in 1654 (Camuffo and Bertolin, 2012). Droughts have already become more common, especially in the tropical and subtropical regions since the 1970s (Meehl et al., 2007). Consistent with precipitation changes, runoff is notably reduced in southern Europe and increased in Southeast Asia and at high latitudes. The larger simulated runoff changes reach a 20% increase compared to 1980 to 1999 mean values. These changes will likely become more apparent in the future (Meehl et al., 2007). Climate changes will mainly impact the contamination sources and pathways of bacteria onto LGVs during the pre-harvest phase. Other phases of the food chain will be less affected, because generally processing and transport are done in controlled environments.

Several studies focus on climate change and foodborne diseases (FAO, 2005; Lafferty, 2009; Rose et al., 2001; Semenza and Menne, 2009). There is also considerable understanding of how climatic variables affect pathogen survival in different environments. However, only few studies (e.g. Miraglia et al., 2009; Moretti et al., 2010; Tirado et al., 2010) have addressed the relationship between climate change impacts and the microbial safety of LGVs. Moretti et al. (2010), for example, qualified the impacts of temperature on post-harvest fresh produce quality from a biochemical perspective and summarised that the crop will mature sooner with higher temperature during the growing season. A systematic overview encompassing the impacts of temperature and precipitation changes on the contamination sources and pathways of bacteria on LGVs is, however, still missing. Such an overview is essential to quantitatively assess the impact of climate change on LGV safety.

This paper therefore aims to review and synthesise major impacts of climate change (temperature increases and precipitation pattern changes) on contamination sources and pathways of foodborne pathogens (focussing on *E. coli* O157 and *Salmonella* spp.) on pre-harvested LGVs. Relevant literature, including peer review scientific papers and grey literature, on LGVs but limited to *E. coli* O157 and *Salmonella* spp., has been studied for each contamination source and pathway, and for their relationship to different climate variables. Each contamination source has been searched in combination with each of these two pathogens, and with temperature and precipitation. In this study, firstly, contamination sources and pathways of *E. coli* O157 and *Salmonella* spp. onto LGVs are identified. These are formulated as a conceptual framework (Section 2). Then we summarised major positive and negative impacts of temperature increases and precipitation pattern changes on pathogen prevalence in each contamination source and pathway (Section 3). Although the reviewed literature and data was relatively limited to Europe and North America, the study aims to provide a generic worldwide overview.

2. Contamination sources and pathways

Two foodborne pathogens will be discussed in this review: *E. coli* O157 and *Salmonella* spp. in general. Different *Salmonella* serotypes will be discussed depending on the literature. This choice was made because these pathogens are the leading cause of bacterial foodborne illness on LGVs and are well documented in many studies (Bach et al., 2002; Beuchat, 1996; Hanning et al., 2009; Maurer and Lee, 2005; Sivapalasingam et al., 2003, 2004). These two pathogens are also representative for other foodborne bacterial pathogens, and their abundant literature will likely result in a deeper analysis.

The contamination sources and pathways associated with LGV contamination with *E. coli* O157 and *Salmonella* spp. form the basis for the conceptual framework (Fig. 1). Beuchat (2006) reviewed the literature for generic contamination sources and pathways for fresh produce. We build on this by summarising these findings and adding more recent literature. The principal reservoir for *E. coli* O157 is cattle and other small ruminants such as sheep and deer (Hancock et al., 2001). The main reservoirs for *Salmonella* spp. are pigs (Fedorka-Cray et al., 2000) and poultry (Aserkoff et al., 1970; Vandeplas et al., 2010). The pathogens shed in the faeces of these animals can subsequently contaminate LGVs directly or indirectly by contamination of soil and water. Additionally, the pathogens can enter the environment via shedding from incidental hosts (e.g. humans and insects) or wildlife. We therefore consider manure, soil, surface water, sewage and wildlife to be the most likely contamination sources.

2.1. Manure

Contaminated manure from livestock and faeces from wildlife form the primary source of environmental contamination with zoonotic pathogens such as *E. coli* O157 and *Salmonella* spp. Livestock and wildlife

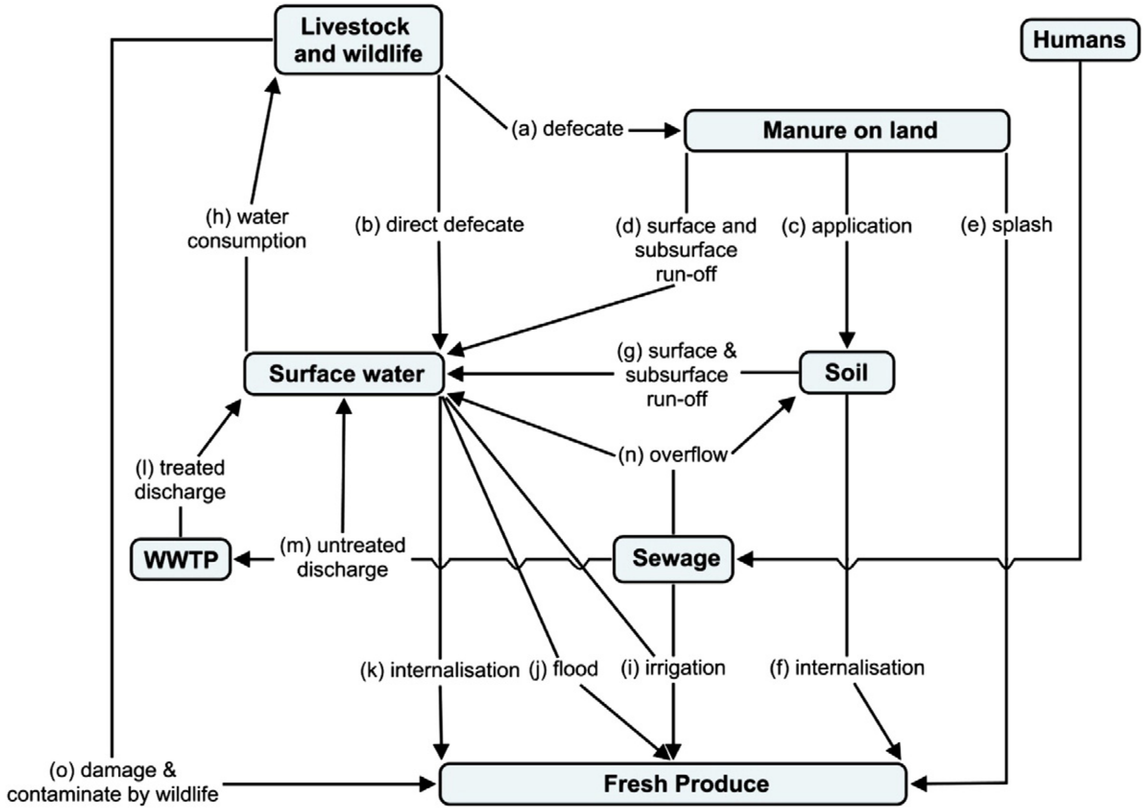

Fig. 1. Bodies and pathways of pathogenic bacteria on leafy green vegetables. Boxes show bodies of pathogenic bacteria, arrows and words in the middle of arrows indicate pathogen flow. WWTP stands for waste water treatment plant. The letters a–o are referred to in the text.

may defecate on land (Fig. 1, arrow a) or directly into surface water (Fig. 1 arrow b). The pathogens in livestock manure are killed by different treatments, such as long-term storage and/or composting. The use of improperly treated manure is an important risk factor for the microbial safety of LGVs (Franz and van Bruggen, 2008; Jiang and Shepherd, 2009). Such livestock manure may contaminate LGVs when applied during plant growth (Fig. 1 arrow c) and by contaminating water supplies (for example surface water) via surface and subsurface runoff (Fig. 1 arrow d) (Jackson et al., 1998). Contamination of LGVs that grow on the manure-amended soils, might occur by splash dispersal (Fig. 1 arrow e) during rain events (Franz et al., 2008b; Madden, 1997; Monaghan and Hutchison, 2012; Pielaat and van den Bosch, 1998).

2.2. Soils

Soil amended with contaminated manure or faeces can be a source of *E. coli* O157 and *Salmonella* spp. which can persist in the soil up to several months (Barak and Liang, 2008; Franz et al., 2008a, 2011; Jamieson et al., 2002; Semenov et al., 2009; Unc and Goss, 2006; Van der Zaag et al., 2010). When plants are grown in contaminated soils internalization (Fig. 1 arrow f) of pathogenic *E. coli* and *Salmonella* spp. via root uptake has been described in laboratory settings (Deering et al., 2012; Franz et al., 2007; Solomon et al., 2002). This process however is thought to be rare in field conditions and, additionally, *E. coli* O157 does not persist in the leaves more than seven days (Erickson et al., 2010a). The evidence for internalisation of *Salmonella* spp. via soil has not been found. *E. coli* O157 (Donnison and Ross, 2009), *Salmonella* spp. *and Salmonella infantis* (Jacobsen and Bech, 2012; Miner et al., 1967) can be transferred by runoff from soils via the surface and subsurface to the surface water (Fig. 1 arrow g).

2.3. Surface water

Cooley et al. (2007) reported that surface water is a possible vehicle of transmission of *E. coli* O157 for pre-harvest LGV contamination. Livestock and wildlife may get (re)infected by consumption of contaminated water (Fig. 1 arrow h). Surface water may not only contaminate fruits and vegetables by irrigation (Bach et al., 2002; Erickson et al., 2010b; Islam et al., 2004a, 2004b; Okafo et al., 2003; Rose et al., 2001; Sivapalasingam et al., 2003; Steele and Odumeru, 2004) (Fig. 1 arrow i) but also as result of flooding (Fig. 1 arrow j) of production fields after (extreme) rain events (Cooley et al., 2007; Orozco et al., 2008).

Like with root uptake from the soil, application of contaminated irrigation water can lead to internalization of both *E. coli* O157 and *Salmonella* spp. into the edible part of LGVs through open stomata (Kroupitski et al., 2009) (Fig. 1 arrow k). Extreme weather conditions (i.e. drought and heavy rains) have been shown to increase the levels of internalized *Salmonella* Typhimurium into lettuce leaves (Ge et al., 2011).

2.4. Sewage

In developing countries and arid regions, sewage is often used for irrigation (Amoah et al., 2005; Nichols et al., 1971; WHO/UNICEF JMP, 2010) (Fig. 1 arrow i). It is cheap and efficient, as sewage also contains a high concentration of bioavailable nitrogen and phosphorus from domestic waste. Normally sewage flows back to surface water after being treated in waste water treatment plant (Fig. 1 arrow l). Untreated sewage (Fig. 1 arrow m) or improperly treated effluents from wastewater treatment plants used for irrigation may contain high levels of pathogens (Gale, 2005; Gerba and Smith, 2005; Nichols et al., 1971). Sewer overflows (Fig. 1 arrow n) may cause many *Salmonella* serotypes (Claudon et al., 1971) and commensal *E. coli* (McLellan et al., 2007) to enter the surface water and/or soil directly.

2.5. Wildlife

Wildlife (e.g. insects, birds and mammals) may carry pathogenic bacteria in their digestive and respiratory systems, skin, hooves and hair or feathers (Ray and Bhunia, 2008; WHO, 2011). These wildlife share similar exposure pathways with livestock (c.f. Fig. 1). Moreover, they might damage the leaves (Fig. 1 arrow o), which provide vulnerable entry points for foodborne pathogens into the plant and leaching of nutrients that will facilitate pathogen persistence (Orozco et al., 2008). The wildlife driven contamination is further excluded from this review, as contamination by wildlife is random and currently unpredictable. This makes quantification very difficult. Moreover, climate change impacts on wildlife are species specific (Mawdsley et al., 2009; McCarthy et al., 2001; Petzoldt and Seaman, 2005; Root and Schneider, 2002). We expect that in the area where LGVs are grown wildlife will remain present under current climate change scenarios even though specific species may vary. Additionally, producers will often attempt to keep wild life out of the fields by fencing or removing vegetation around the field.

2.6. Summary

Contamination sources and pathways vary depending on the practical farming management in different parts of the world. In general, manure amended soil and irrigation water are better studied sources.

3. Influence of climate variables

Climate is commonly defined as the weather averaged over a long time. The standard averaging period is thirty years. As mentioned in the introduction, the incidence of foodborne disease is related to climatic conditions. Temperature and precipitation patterns and other climate factors are expected to change due to an increase in the radiation balance of the earth caused by greenhouse gas emissions. Standard practice in climate research is the application of different scenarios. These scenarios comprise plausible changes in factors driving climate change, such as population growth and land use changes. Climate models are run for these different scenarios to determine projected changes in climate variables worldwide. These changes differ by scenario and region, but generic changes are as follows:

- Modelling studies project that temperature will continue to increase gradually over time, resulting in a 2 °C to 5 °C increase of 1-in-20 year extreme daily maximum temperature by the late 21st century (IPCC, 2012). Highest temperature increases will be over land and at high northern latitudes (Fig. 2, IPCC, 2007).
- The amount of precipitation is expected to increase in some areas (e.g. high latitude and tropical regions, and in winter in the northern mid-latitudes) and decrease in others (e.g. southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa) (IPCC, 2012) (Fig. 3, Meehl et al., 2007). Moreover, the distribution of precipitation is expected to change, resulting in an increase in the number of extreme precipitation events even in areas with decreasing precipitation (IPCC, 2012; Meehl et al., 2007). The characteristics of what is called extreme weather may vary from place to place. But an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile (IPCC, 2007). These events might intensify floods or droughts in some catchments, areas and seasons (IPCC, 2012). This has already been observed in several regions (Meehl et al., 2007).
- Due to temperature and precipitation changes, evapotranspiration changes affect atmosphere and soil moisture. Increased land precipitation intensity together with increased temperature lead to a higher moisture content of the atmosphere at a rate of about 7% for every 1 °C rise (Trenberth et al., 2007). The annual mean soil moisture decreases in the subtropics and the Mediterranean region and increases in east Africa, central Asia, and some other regions with increased precipitation (Meehl et al., 2007). We discuss soil humidity changes together with precipitation changes.
- Ultraviolet (UV) radiation is another variable that impacts bacterial contamination of LGVs and that is influenced by climate change. UV radiation changes have been simulated by radiative transfer models for all IPCC scenarios. The amount of UV at the surface result from ozone concentrations in the upper troposphere and lower stratosphere, cloud cover and the aerosol type, content and distribution (Penner et al., 1999). Under clear skies, UV light can effectively kill microbes (Yaun et al., 2003). Cloud cover, however, is very difficult to predict due to geometrical complexity and temporal variability of clouds (Penner et al., 1999; Sausen et al., 2005). Future UV changes on foodborne pathogens will therefore not be further discussed in this paper.

Climate change may impact on the contamination sources and pathways of *E. coli* O157 and *Salmonella* spp. These impacts may increase the likelihood of LGV contamination and human disease associated with consumption of contaminated LGVs. Climate change may, therefore, increase the risk of disease due to foodborne contamination. Seasonality of the human prevalence of infections (mostly acquired through direct contact with animals or manure, and increasingly through consumption of raw vegetables) indicates climate change impacts (see introduction). The *E. coli* O157 incidence of human disease is generally higher in summer months and early fall (Douglas and Kurien, 1997; Rangel et al., 2005; Van Duynhoven et al., 2004) and the daily *Salmonella* incidence closely follows ambient temperature with the a lag of 2 to 14 days (Naumova et al., 2007). However, the causal mechanisms behind the seasonal patterns remain elusive and may vary among different pathogens and geographic regions due to several confounding factors (e.g. animal housing, diet). Furthermore, there may be heterogeneity between strains of a particular pathogen. For instance, some strains may be better adapted to higher temperatures or tolerate drier conditions, which may enhance their environmental survival capacities and ultimately the likelihood of LGV contamination (Franz et al., 2011).

From this literature review the relationship between climate change and contamination sources and pathways of *E. coli O157* and *Salmonella* spp. is evident. The next section discusses for each source of both pathogens first possible impacts of temperature and then possible impacts of precipitation. Manure and soil are combined as the climate change impacts on these sources are similar. Also the important seasonal relationships are discussed. Table 1 summarises all impacts.

3.1. Manure and soil

3.1.1. Temperature

3.1.1.1. Seasonality of E. coli O157 in livestock. Many studies are available on the seasonal patterns of *E. coli* O157 prevalence among livestock, from which general relations between temperature and pathogen prevalence and/or shedding rates can be deduced. Ultimately these relations can be used, to a certain extent, to predict the likelihood of having contaminated manure. Since the causal relations remain unclear, these have not been explicitly added to Fig. 1. Higher prevalence and/or increased shedding rates have been observed in cattle during summer months (Berends et al., 2008; Heuvelink et al., 1998; Hussein and Sakuma, 2005; Ogden et al., 2006; Schouten et al., 2005). The role of temperature in the seasonality of *E. coli* O157, however, has been questioned: The North-American latitudinal gradient of *E. coli* O157 prevalence, for example, showed an opposite relation to the temperature gradient (Meyer-Broseta et al., 2001). Seasonality has also been observed in regions with little seasonal temperature fluctuations (Miller et al., 2004). Interestingly, a strong correlation between increased day length and *E. coli* O157 prevalence in cattle was observed in North America

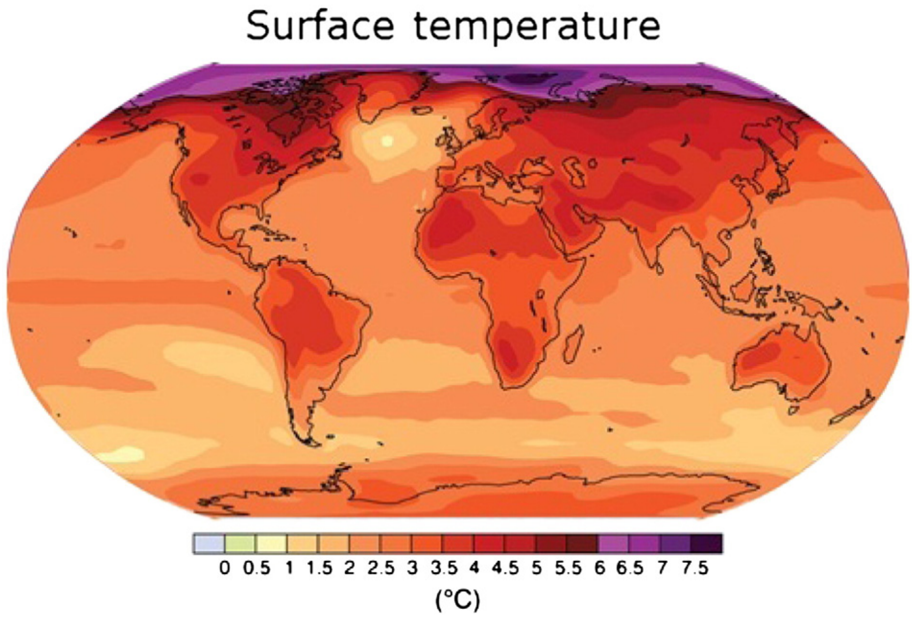

Fig. 2. Multi-model mean projections of changes in surface air temperature (°C). Changes are annual means for the SRES A1B scenario for the period 2090 to 2099 relative to 1980 to 1999. General Circulation Models, representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. Key assumptions of SRES A1B scenarios: a future world with very rapid economic growth, low population growth, rapid introduction of new and more efficient technology and balanced energy sources. Credit: Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure spm6. Cambridge University Press.

(Edrington et al., 2006). This, is unlikely to be affected by climate change. This indicates that indeed also other factors may be involved.

3.1.1.2. Seasonality of Salmonella in livestock. In the US, the occurrence of *Salmonella* on dairy farms increases with increasing seasonal temperature (Pangloli et al., 2008). In Denmark, the seasonal variation of the prevalence in pork and the human incidence is similar (Hald and Andersen, 2001). However, several factors, such as management practices, concurrent diseases and elevated temperatures that lead to stress and higher multiplication rates of *Salmonella*, could well cause seasonal trends (Hald and Andersen, 2001). *Salmonella* prevalence in Danish finisher pig herds was also higher in summer and fall as compared to spring and winter (Baptista et al., 2009).

3.1.1.3. Direct effects of climate change on environmental fate of E. coli O157 and Salmonella. Weather conditions influence transport and dissemination of pathogens from their reservoirs into the environment, food crops like LGVs and other hosts. Higher soil temperatures may

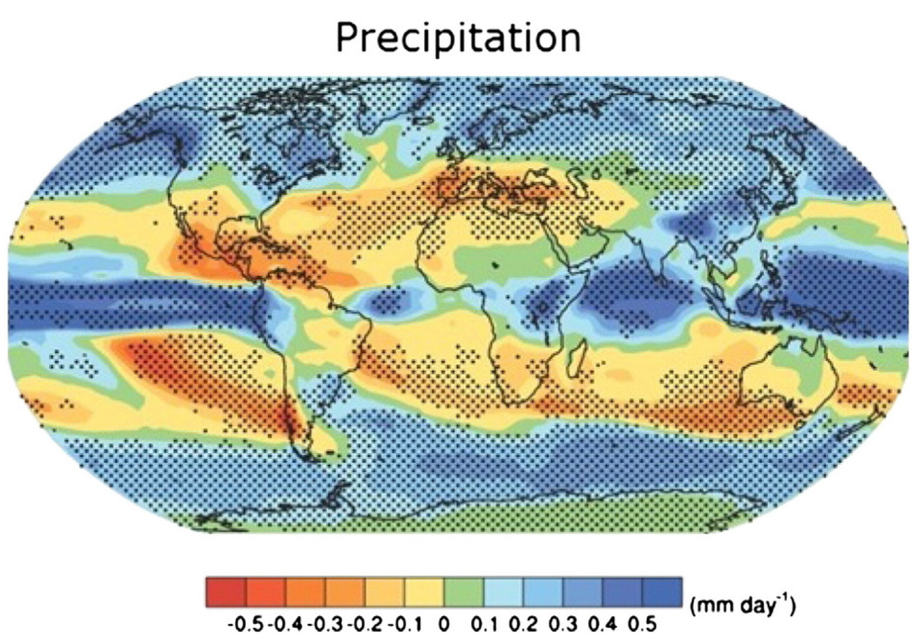

Fig. 3. Multi-model mean projections of changes in precipitation (mm day^{-1}). Changes are annual means for the SRES A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Regions are dotted where at least 80% of models agree on the sign of the mean change. General Circulation Models and key assumptions of SRES A1B scenarios are referred to in Fig. 2. Credit: Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 10.12. Cambridge University Press.

Table 1
The influence of climatic changes on contamination pathways and pathogens survival.

Climate variables	Contamination sources	Relationship*	Changes	Pathogens	Reference
Temperature	Manure & soil	+	a) Use of manure		Franz et al. (2008a)
		−	b) Survival of pathogens in manure and soil	*E. coli* O157:H7	Himathongkham et al. (1999), Kudva et al. (1998), Mukherjee et al. (2006), Semenov et al. (2007) and Wang et al. (1996)
				Salmonella	Danyluk et al. (2008), Himathongkham et al. (1999) and Semenov et al. (2007)
	Surface water	−	c) Survival of pathogens	E.coli O157:H7	Wang and Doyle (1998)
				Salmonella	Rhodes and Kator (1988)
	Sewage	−	d) Survival of pathogens	*E. coli* O157:H7**	
				Salmonella	Wolna-Maruwka et al. (2009)
Precipitation	Manure & soil	+	e) Survival of pathogens in manure and moist soil	*E. coli* O157:H7	Warriner (2005) and Warriner et al. (2009)
				Salmonella	Warriner (2005) and Warriner et al. 2009
		+	f) Chance of splash		Cevallos-Cevallos et al. (2012), Franz et al. (2008b) and Madden et al. (1996)
	Surface water	−	g) Amount of irrigation water		
		+	h) Surface and subsurface run-off		
		+	i) Chance of flood		Donnison and Ross (2009) and Orozco et al. (2008)
	Sewage	+	j) Chance of sewage overflow		Tierney et al. (1977) and Watkins and Sleath (1981)
		−	k) Concentration of waste water in surface water stream		Hofstra (2011) and Senhorst and Zwolsman (2005)
		−	l) use of sewage as a source of water and nutrients		

* +/− explains the positive/negative relation between the columns "Climate variables" and "Changes". For example, e) precipitation is positively correlated with survival of pathogens in manure and moist soil. So, survival of pathogens in manure and moist soil will increase with increased precipitation and decrease with decreased precipitation.
** The relationship between survival of *E. coli* O157:H7 in sewage and increased temperature is unclear.

lead to an increased use of potentially contaminated animal manure due to a faster depletion of soil nutrients as a result of increased biological soil activity (Franz et al., 2008b) (Table 1, a).

Temperature increase has a close relationship with foodborne bacteria growth and survival (Beuchat, 2002; Beuchat and Mann, 2008; D'Souza et al., 2004; FAO, 2008; Franz and van Bruggen, 2008; Himathongkham et al., 1999; Jiang et al., 2002; Lake et al., 2009; Mukherjee et al., 2006; Nelson, 2009; Pan and Schaffner, 2010; Ratkowsky et al., 1982). Although commensal *E. coli* has been found to establish a stable population in the soil environment (Byappanahalli and Fujioka, 2004; Ishii et al., 2006), the conditions for survival of foodborne pathogens are considered to be unfavourable once excreted from the animal gut. However, pathogens like *E. coli* O157 and *Salmonella* spp. are able to survive for extended periods (up to months) in manure and soil (Franz et al., 2008a). The survival of *E. coli* O157 and many *Salmonella* serotypes in soil and manure decreases with increasing temperature (Danyluk et al., 2008; Himathongkham et al., 1999; Kudva et al., 1998; Mukherjee et al., 2006; Semenov et al., 2007; Wang et al., 1996) (Table 1, b). The main reason for this inverse relation between temperature and persistence in soils is the increased levels of microbial competition due to increased (metabolic) activity of the native microflora (Semenov et al., 2007).

3.1.1.4. Indirect effects of climate change on the ecology of E. coli O157 and Salmonella. Several indirect effects of climate change can be defined. Higher temperatures might lead to increased susceptibility of livestock to animal disease. This, might make them more vulnerable to (asymptomatic) colonization by human enteric pathogens. Higher temperatures might also affect feeding strategies which can have a profound effect on the prevalence and shedding rate of human pathogens by altered ecological conditions in the animal gut (Jacob et al., 2009). Direct or indirect effects of climate might also affect the super-shedding phenomenon (i.e. some cattle may harbour and shed bacteria at higher levels that others), which strongly influence dissemination pathogens into the environment and ultimately to humans (Matthews et al., 2006). In addition, with higher temperatures cattle may graze more outside where they are more exposed to pathogens. They then feed on grass, which affects survival and shedding rates (Jacob et al., 2009). These indirect effects are not considered and thus not summarised in Table 1.

3.1.2. Precipitation for E. coli O157 and Salmonella

The impact of precipitation on bacteria contamination of manure and soil is relatively limited. Increased land precipitation intensity together with increased temperature lead to a higher moisture content of the atmosphere at a rate of about 7% for every 1 °C rise (Trenberth et al., 2007) and a higher soil moisture content. Such higher air and soil humidity could enhance survival of pathogens in moisturised soil and manure (Warriner, 2005; Warriner et al., 2009) (Table 1, e).

Higher intensity of rain events also enhance the chance of splashing manure and soil particles to fresh produce (Cevallos-Cevallos et al., 2012; Franz et al., 2008b; Madden et al., 1996) (Table 1, f).

3.2. Surface water

3.2.1. Temperature for E. coli O157 and Salmonella

Generally pathogen cell numbers decline over time when added to surface water (Vital et al., 2008). *E. coli* O157, however, has been observed to grow in surface water at 30 °C with low carbon concentration (Vital et al., 2008). The survival of both *E. coli* O157 and *Salmonella* spp. in surface water decreases with increasing temperatures (Rhodes and Kator, 1988): the survival of *E. coli* O157 in surface water is up to 13 weeks at 8 °C (Wang and Doyle, 1998) and it strongly decreases with increasing temperatures. But it can still survive up to 8 weeks at 25 °C (Wang and Doyle, 1998) (Table 1, c). An unusually prolonged outbreak in the summer of 1991 of bloody diarrhoea and hemolytic–uremic syndrome caused by *E. coli* O157 was traced to shallow swimming water (Keene et al., 1994). This outbreak suggests that these foodborne pathogens survive in lake water. Survival of *Salmonella* spp. is greater than that of *E. coli* (the faecal indicator) in surface water. In low water temperatures (less than 10 °C), more than 83% of salmonellae survived after 1 week compared to less than 6% of *E. coli* during the same period (Rhodes and Kator, 1998) (Table 1, c).

3.2.2. Precipitation for E. coli O157 and Salmonella

Increased temperatures and decreased precipitation enhance evapotranspiration (Meehl et al., 2007). This results in an increased need for irrigation of crops (Table 1, g). On the other hand, water scarcity in dry regions may result in future technological and management changes, such as subsurface drip irrigation instead of overhead sprinkler (Fonseca et al., 2011) or new water treatment methods which have lower contamination risk. Such technological changes may lower the risk of contamination via irrigation water.

Intensive precipitation may increase surface and subsurface runoff, which might be an intermediate contamination pathway of pathogens from manure at livestock farms and from grazing pastures (Table 1, h). When crops are irrigated with this water, contamination might be increasing.

Flooding as a result of extreme precipitation events can bring pathogens from surface water to fresh produce and might contaminate whole fields (Donnison and Ross, 2009; Orozco et al., 2008) (Table 1, i).

3.3. Sewage

The impact of temperature on pathogen survival in sewage water is very limited. Decreased cell numbers of the *Enterobacteriaceae* family and *Salmonella* genus have been observed with temperature increase (Wolna-Maruwka et al., 2009) (Table 1, d). The die-off of commensal *E. coli* and *Salmonella* spp. in wastewater is related to desiccation of the sewage and was faster in warmer and drier conditions (Horswell et al., 2007).

Heavy rainfall in a relatively short time could cause sewer overflows to surface water and/or soil (Tierney et al., 1977; Watkins and Sleath, 1981) (Table 1, j). This increases the risk of contaminated irrigation water. In drought-prone regions, the dilution of sewage in streams is reduced when surface water discharge decreases. So the concentration of pathogens in the surface water increases. This, increases the concentration of pathogens in the surface water (Hofstra, 2011; Senhorst and Zwolsman, 2005) (Table 1, k). In addition, a shortage of irrigation water and the high costs of artificial fertilizer may increase the use of sewage as a source of water and nutrients (Table 1, l).

4. Concluding remarks

The objective of this paper was to review and synthesise major impacts of climate change (temperature increases and precipitation pattern changes) on contamination sources and pathways of foodborne pathogens (focussing on *E. coli* O157 and *Salmonella* spp) on pre-harvested LGVs.

Contamination sources (e.g. soil, manure, water, etc.) and pathways (irrigation, splash, contact with faeces, etc.) of *E. coli* O157 and *Salmonella* spp. onto LGVs were identified. Then the positive and negative impacts of temperature increases and precipitation pattern changes on pathogen prevalence in each contamination source and pathway have been elaborated.

Temperature likely increases everywhere, but precipitation patterns differ largely by region. Already arid regions are expected to become drier, whilst wet regions are expected to become wetter and extreme precipitation events are expected to occur more often worldwide. These changes have both positive and negative impacts on contamination sources and pathways that influence *E. coli* O157 and *Salmonella* spp. survival in manure, soil and water.

Whether climate change increases the prevalence of *E. coli* O157 and *Salmonella* spp. on pre-harvest LGVs depends on the balance of the positive and negative impacts and on the applied climate change scenarios for specific areas. There are, however, to date no quantitative studies assessing this balance and talking into account all positive and negative impacts. This review shows the need for quantitative modelling approaches with scenario analyses to understand the net impact of climate change on the contamination of pre-harvested LGVs. Also additional laboratory experiments, such as splash tests for both pathogens and LGVs and contamination of LGVs after irrigation with contaminated surface water — issues that appear to be missing from the literature-, would aid our understanding.

This study gives an innovative and extensive overview of the impacts of climate change on the contamination of pre-harvested LGVs. Although the balance of positive and negative impacts requires further study, this review clearly shows that climate change should not be ignored in food safety management and research.

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