Science of the Total Environment 539 (2016) 583–591

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Rainfall intensity effects on removal of fecal indicator bacteria from solid dairy manure applied over grass-covered soil

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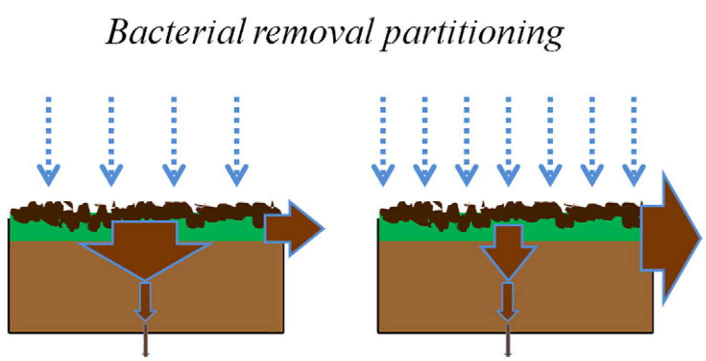
HIGHLIGHTS

- Release and removal of indicator bacteria from manure was evaluated in soil boxes.
- Rainfall intensity did not impact runoff-removal kinetics in three tested models.
- Rainfall intensity had positive/inverse effects on bacterial release to runoff/soil.
- Total release was significantly greater for *E. coli* than for enterococci.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 May 2015
Received in revised form 30 June 2015
Accepted 23 July 2015
Available online 18 September 2015

Editor: D. Barcelo

Keywords:
Microbial release
Dairy manure
Rainfall intensity
E. coli
Enterococci
Runoff and infiltration

ABSTRACT

The rainfall-induced release of pathogens and microbial indicators from land-applied manure and their subsequent removal with runoff and infiltration precedes the impairment of surface and groundwater resources. It has been assumed that rainfall intensity and changes in intensity during rainfall do not affect microbial removal when expressed as a function of rainfall depth. The objective of this work was to test this assumption by measuring the removal of *Escherichia coli*, enterococci, total coliforms, and chloride ion from dairy manure applied in soil boxes containing fescue, under 3, 6, and 9 cm h^{-1} of rainfall. Runoff and leachate were collected at increasing time intervals during rainfall, and post-rainfall soil samples were taken at 0, 2, 5, and 10 cm depths. Three kinetic-based models were fitted to the data on manure-constituent removal with runoff. Rainfall intensity appeared to have positive effects on rainwater partitioning to runoff, and removal with this effluent type occurred in two stages. While rainfall intensity generally did not impact the parameters of runoff-removal models, it had significant, inverse effects on the numbers of bacteria remaining in soil after rainfall. As rainfall intensity and soil profile depth increased, the numbers of indicator bacteria tended to decrease. The cumulative removal of *E. coli* from manure exceeded that of enterococci, especially in the form of removal with infiltration. This work may be used to improve the parameterization of models for bacteria removal with runoff

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http://dx.doi.org/10.1016/j.scitotenv.2015.07.108
0048-9697/Published by Elsevier B.V.

and to advance estimations of depths of bacteria removal with infiltration, both of which are critical to risk assessment of microbial fate and transport in the environment.

1. Introduction

The release of manure-borne pathogens during rainfall frequently leads to the impairment of environmental water resources. Microbial release and removal from manure are affected by management-reflecting variables, such as, manure application rates (Brooks et al., 2009; Drapcho, 2003), allotted times for cattle to graze on pasturelands (Edwards et al., 2000), duration of the manure aging period (Kress and Gifford, 1984), and method of manure application (Forslund et al., 2011; Sistani et al., 2010), as well as by environmental conditions, such as, vegetation status (Dao et al., 2008; Guber et al., 2006, 2007; Roodsari et al., 2005) and soil water contents at the application site (Cardoso et al., 2012), animal source (Hodgson et al., 2009; Soupir et al., 2003; Thurston-Enriquez et al., 2005) and corresponding water contents of waste (Hodgson et al., 2009), and dissolved salts in rainwater (Bradford and Schijven, 2002). The majority of waterborne disease outbreaks in the United States from 1948 to 1994 were preceded by extreme precipitation events above the 90th percentile (Curriero et al., 2001); that is, rainfall is a leading factor impacting microbial release and transport that leads to human exposure (Bradford and Schijven, 2002; Hodgson et al., 2009; Forslund et al., 2011). Understanding the effects of rainfall intensity on non-point source pollution is critical, especially with an expectation that intensive precipitation events will become more variable with climate change (Liu et al., 2013).

The rainfall intensities that have been used in the culmination of published microbial release and removal studies (n = 31) have ranged from 1.4 to 11 cm h^{-1}, simulating frequently occurring, light rainfall events as well as extreme, thunderstorm-like events (Blaustein et al., 2015a); however, the literature in which water application intensity was a controlled variable is limited (Kress and Gifford, 1984; Schijven et al., 2004). In two studies on the removal of *Cryptosporidium* from manure applied to soil, Forslund et al. (2011) and Boyer et al. (2009) observed recovery rates of approx. 0.05% and 0.12–0.27% under rainfall intensities of 0.48 cm h^{-1} and 2.8 cm h^{-1}, respectively. Forslund et al. (2011) suggested that the differences in measured recovery rates had been caused by the different rainfall intensities that were applied. Schijven et al. (2004) reported *Cryptosporidium* oocyst release efficiencies from cattle "manure discs" to be greater under dripping- than misting water applications and for the efficiencies to be positively affected by the intensity of applied mist. The authors suggested that rainfall events with higher intensities should increase the numbers of manure-borne microorganisms released on a farm. Although water application intensity may positively affect microbial release numbers, the concentrations of microorganisms in runoff during higher-intensity rainfall events could actually end up being relatively low due to dilution by rainwater. A study on bacterial release from cowpats in a pan revealed that variations in rainfall intensity (2.3, 5.1, and 6.9 cm h^{-1}) had significant impacts on the peak concentrations of fecal coliforms in runoff coming from 20-day-old cowpats, but not from fresh cowpats (Kress and Gifford, 1984). There is currently no published study on the effects of rainfall intensity on microbial release and removal from manure that is applied to soil.

Kinetic-based microbial release/removal models allow for simulating the total numbers of released/removed microorganisms and the concentrations in suspension (Blaustein et al., 2015a). These models can be written as dependencies of release/removal on the rainfall depth, with the assumptions that knowing the total amount of applied water provides sufficient information for making simulations and that rainfall intensity and changes in rainfall intensity during rainfall do not affect the simulated results (Bradford and Schijven, 2002; Blaustein et al., 2015a; Guber et al., 2006, 2013; Schijven et al., 2004). To our knowledge, no studies have evaluated the effects of rainfall intensity on microbial removal model parameters. In addition, it is not clear whether such models should account for total rainfall depth or only rainfall depth after runoff begins. During rainfall–runoff events, applied water has to be partitioned between a period before and a period after runoff initiation, and the duration of this lag period relies on initial soil hydrologic conditions (Cardoso et al., 2012). For example, in 144 experimental rainfall simulations at field plots in Watkinsville, GA, varying antecedent soil moisture conditions caused large differences in runoff start times (Kim et al., 2014). Runoff generation time may also depend on the dryness of animal waste and the amount of rainfall that will induce release (Thelin and Gifford, 1983). The manner in which to correctly use rainfall depth in microbial removal models needs further clarification.

The objectives of this work were to conduct rainfall–runoff experiments with dairy manure applied in soil boxes to evaluate the effects of rainfall intensity on: a) the removal of manure-borne *Escherichia coli*, enterococci, total coliforms, and chloride ion with runoff, b) the amounts of indicator bacteria removed with infiltration to different soil profile depths, and c) the total release of indicator bacteria from manure.

2. Methods

2.1. Soil boxes

Soil boxes (100 × 35 × 15 cm) were constructed, packed with soil, and seeded with fescue (Isensee and Sadeghi, 1999; Sadeghi and Isensee, 2001). Each box was equipped with one height-adjustable runoff drain (10 mm diam.) positioned at the front of the box and three leachate drains (6 mm diam.) positioned at the center of the base at 1 cm, 34 cm, and 67 cm up from the front of the box. A mesh screen (1 mm^2 openings) was set over each leachate drain in order to prevent clogging. Two aluminum angle partitions (14 mm height) were attached to the base of each box directly in front of the 34- and 67-cm leachate drains to aid in the collection of sectioned leachate.

Packing soil into the boxes was done in layers to establish uniform bulk density (Isensee and Sadeghi, 1999; Sadeghi and Isensee, 2001). Each box received an initial layer of 7 kg of air-dried sand (≤2 mm) that was evenly spread across the base, packed with a 20 × 20 cm plywood board, and lightly grooved at the surface with a hand-cultivator tool. Over the sand, a 7 kg layer of air-dried A-horizon soil, which had been screened for rocks and gravel and treated with lime, was poured into the box, evenly spread, packed with the plywood board, and grooved at the surface. Six more layers of topsoil were added by this method.

Soil boxes were set in a temperature-controlled hoop house at 18 °C located at the USDA-ARS North Farm in Beltsville, MD. Kentucky 31 tall fescue seed was applied to each box at the rate of 98 g m^{-2} and 2 kg of topsoil was added over the seed. The soil bulk density, after settling, was estimated to be 1.34 ± 0.07 g cm^{-3} (mean ± SE, n = 18 boxes). Boxes were watered 2× a day until germination, then 1× a day for 20 days, and then 1× a day every two or three days until experimentation. Grass blades were trimmed to a height of 7.5 cm on a biweekly basis with a hand-held turf trimmer (model gs500; Back and Decker, Towson, Maryland) and excess trimmings were removed by hand. Grass was grown in the hoop house for approximately three months.