Nitrogen (N) loss from dairy farming systems contributes to environmental concerns such as air pollution (ammonia [NH₃] and nitrous oxide [N₂O] emissions) and water quality impairment (primarily nitrate [NO₃] leaching and runoff). Due to a predominance of small farms in the area, many dairy operations in the Chesapeake Bay watershed have limited capacity for manure storage. Dou et al. (2001), in a survey of dairy farms in Pennsylvania, found that 30% had no storage other than in the barn and that manure was often spread daily. For those with storage, the capacity was normally limited to a 6-mo period, allowing for application in the spring and fall. There is pressure to expand manure storage on Pennsylvania dairy farms, but construction costs, logistical concerns (applying a large amount to stored manure over a short time in the spring), and uncertain environmental outcomes have deterred widespread development.

Efforts have also been made to expand manure injection in the Chesapeake Bay watershed because broadcast application is associated with greater nutrient losses to water and air (Verbree et al., 2010, Dell et al., 2011, Maguire et al., 2011). Manure injection has also been part of subsidy programs to increase adoption (e.g., Environmental Quality Incentives Program, USDA Natural Resources Conservation Service).

We sought to assess trade-offs in economics and N fate from alternative manure management options for dairy farms. The objectives of this study were (i) to compare environmental losses and N budgets associated with broadcast applied manure and management with shallow disk injected manure, (ii) to identify the economic implications of moving from broadcast to injection systems, and (iii) to elucidate the role of manure storage in environmental, agronomic, and economic outcomes.

Abstract: Application of livestock manure to farm soils represents a priority nutrient management concern in the Chesapeake Bay watershed. Historically, strong emphasis has been placed on adding manure storage to dairy operations, with the recognition that manure application methods can be improved. The Integrated Farm System Model was used to simulate manure management on a typical Pennsylvania dairy farm (100 milking cows, 80 ha). Converting the operation from daily haul to 6 mo of storage with broadcast application did not substantially change nitrogen (N) losses to the environment. However, switching to manure injection conserved ammonium N and improved manure N use efficiency by crops, even though it increased N leaching by 27% with 6-mo storage and 13% with 12-mo storage. Increasing manure storage from 6 to 12 mo with manure injection reduced nitrate N leaching by 38%, due to better timing of manure application to crop growth, but lowered annual net returns. Overall, manure injection and 6 mo of storage resulted in the best combination of profit and environmental outcome.

Abbreviations: IFSM, Integrated Farm System Model; NUE, nitrogen use efficiency.
Materials and Methods

The Integrated Farm System Model (IFSM) was used to simulate two manure application methods and their respective impacts on nutrient use efficiency (NUE), farm nutrient balances, and manure application methods at a whole-farm scale over 25 yr of weather. The model simulates animal production, feed storage and use, manure handling and nutrient management, and crop production and harvest on a daily time-step (Rotz et al., 2015). It has been used extensively to predict environmental and economic outcomes of different dairy farm management strategies; details on input data, routines, and verification efforts can be found in numerous publications (Rotz et al., 1999, 2002, 2006, 2014; Garcia et al., 2008; Powell and Rotz, 2015). A typical 100-cow Pennsylvania dairy farm was simulated to assess the outcome of implementing manure management practices that are recommended under the Chesapeake Bay Watershed Implementation Plans (Supplemental Material 1).

Scenarios were developed to evaluate a gradient of manure storage capacities and their interaction with field application methods including no storage or daily haul, 6 mo storage with and without manure injection, and 12 mo storage with and without manure injection. The manure was removed from the barn daily and stored as slurry for up to 6 or 12 mo in an aboveground, bottom-loaded tank. For the 6-mo storage scenario, broadcast and disk injection applications were simulated in the spring and fall, whereas for the 12-mo storage, manure was applied once in the spring before planting.

For all farm simulations, 75% of the manure was applied to corn (Zea mays L.), 25% to the rye (Secale cereal L.) cover crop, which decomposed in the spring, contributing to the corn in the following growing season, and none to alfalfa (Medicago sativa L.). The manure was applied at even rates for each crop. The 75% of available manure that was designated for corn, for example, was applied to all 60 ha of corn at the same rate of application. Cropland that was double cropped with rye contributed additional N when the mulched cover crop decomposed in the spring. Starter fertilizer (7–21–7, N–P–K) was applied to the corn at a rate of 15 kg N ha⁻¹, while the alfalfa received no commercial fertilizer. The system was managed under no-till practices common to Pennsylvania dairy farms.

Field N management was designed to support a crude protein content of harvested silage of 7.8%, which is within the optimal range for dairy cattle feeding (7.2–10%) (Roth and Heinrichs, 2001). When manure management scenarios could not achieve 7.8% crude protein due to high N losses, side-dressed fertilizer was added to increase available soil N and the crude protein content in the silage.

Economics

Custom manure haulers charge an average of $88.80 h⁻¹ to broadcast apply dairy slurry manure in central Pennsylvania (USDA-NASS, 2014). Shallow disk injection cost estimates were based on an increase of cost over the broadcast application hourly rate. Shallow disk injection would cost approximately $130.80 h⁻¹ (R. Meinen, personal communication, 2016). Manure storage design and costs followed Pennsylvania State NRCS Engineering standards (P. Vanderstappen, personal communication, 2015) $230,000 for a 12-mo concrete storage tank (~5,317,250 L) and $138,000 for a 6-mo concrete storage tank (~2,658,625 L).

Model Verification

Results from the IFSM were compared with field-scale monitoring of N cycling under experiments comparing broadcast and injection (Duncan, 2016). The IFSM can be used as a “farm field” model in which only the field component of the farm is simulated. This allowed for verification of IFSM predictions with field data. Farm field simulations were developed to closely reflect the conditions of the field experiments. A 10-ha field with a corn silage and rye cover crop rotation was simulated, with all manure imported to the farm and all silage exported. The field received both spring and fall manure applications.

Results and Discussion

Verification of the Integrated Farm System Model

Field measurements were generally consistent with IFSM predictions, particularly for crop yields as well as for most N outputs (Supplemental Table S1). Notably, IFSM predictions of environmental N losses were much better aligned for broadcast application of manure than they were for manure injection. The IFSM appeared to be more sensitive to the effects of management on environmental losses of N, compared with field measurements. The largest difference between modeled and measured data was in the greater prediction of NO₃ leaching losses by the IFSM. In this case, the monitoring methods used for the field study may have underestimated NO₃ leaching as they focused on shallow lateral flow rather than vertical leaching losses from the field.

Effects of Different Manure Storage Capacities

When Manure Is Broadcast

The construction of manure storage is seen as a first step in improving manure handling and field management on dairy farms. Converting a 100-cow dairy from daily haul conditions to 6 mo of manure storage with broadcast application did not improve the reactive N footprint (total of all forms of reactive N loss per unit of milk produced [Rotz et al., 2015]) of the operation (Table 1) and even increased that footprint slightly (from 9.2 to 10.3 g N kg⁻¹ milk produced). It was only when a full year of storage was added to the operation that the reactive N footprint returned to that observed under daily haul, highlighting the trade-offs associated with manure N management.

The addition of manure storage substantially shifted the pathways of environmental losses of N: from losses dominated by NO₃ leaching from manure-amended soils under a daily haul setting to losses dominated by NH₃ volatilization under both 6- and 12-mo storage when manure is broadcast. Under daily haul conditions, NO₃ losses accounted for 60% of the total N losses to the environment. Leaching losses declined to 47 and 42% of total environmental N losses, respectively, with 6 and 12 mo of storage. In part, the
changes in NO₃ leaching with the addition of manure storage reflect greater NH₃ loss with broadcast application of stored manure slurries, as described below, and less manure N available for leaching. In addition, the increase in NO₃ leaching under 6 mo of manure storage relative to 12 mo of storage could be attributed to manure applications in the spring and fall (6-mo storage) as opposed to spring only (12-mo storage), where fall manure is more susceptible to leaching losses (Gangbazo et al., 1995; Gupta et al., 2004; van Es et al., 2006).

For daily haul operations, NH₃ losses were relatively small (36 kg N ha⁻¹), accounting for 36% of total environmental N loss, but these volatile losses increased to 52 kg N ha⁻¹ with 6 mo of manure storage (49% of total N loss). Because manure was broadcast in both the daily haul and manure storage operations, differences in NH₃ volatilization may be attributed to a combination of storage losses and the rate and timing of the applied manure. With daily haul, the amount of manure applied at any time is less than the stored manure applied once or twice a year, and manure spread in winter emits less ammonia than in the spring and fall due to colder temperatures. (Brunke et al., 1988; Meisinger and Jokela, 2000). Expanding storage to 12 mo substantially lowered NH₃ losses relative to 6 mo of storage, but they remained 9 kg N ha⁻¹ greater than for NH₃ emissions predicted for daily haul. The lesser losses compared with 6 mo of storage are likely due to the seasonal timing of manure application, with less emission in the cooler spring temperatures before planting than in late summer or fall after harvest.

Although N₂O accounted for a tiny fraction of total environmental N losses (<3%), small differences were observed between the daily haul operation and the 6- and 12-mo storage operations with broadcast manure. The greatest losses were with daily hauling of manure, likely reflecting timing of manure application around periods of greater denitrification potential. Elsewhere, Duncan et al. (2017) observed greater emissions 7 to 10 d after manure application and slightly smaller increases in emissions with precipitation events later in the corn-growing season.

### Coupling Manure Injection with Manure Storage

Manure application by injection resulted in the smallest reactive N footprints. Compared with the reactive N footprint of the daily haul operation (9.2 g N kg⁻¹ milk produced), a comparable farm with 6 mo of storage and injection had a footprint of 8.3 g N kg⁻¹ milk produced, while a farm with 12 mo of storage and injection had a reactive N footprint of 7.1 g N kg⁻¹ milk. Previously, Powell and Rotz (2015) reported reactive N footprints of 6.9 to 8.9 g N kg⁻¹ milk for dairy farms where either all of the feed was produced on the farm or only the forage was produced on the farm. Therefore, the Pennsylvania farm simulated in this study had a relatively similar footprint.

The greatest benefit to the addition of manure injection to farms with manure storage is seen with NH₃ emissions from manure-amended soils. Ammonia emissions following injection were at least 89% lower than those predicted under daily haul management and were as much as 92% lower than those predicted from farms with manure storage where manure was broadcast. This represents the well-established benefit of manure incorporation on NH₃-N conservation (Duncan et al., 2017). Expanding manure storage from 6 to 12 mo resulted in a very small change from 3.7 to 3.5 kg N ha⁻¹, reflecting the dominant effect of injection on NH₃ loss relative to the benefits tied to differences in manure application timing.

The IFSM did predict some trade-offs with NO₃ leaching and manure injection. Compared with daily haul, 6-mo storage increased NO₃ leaching by 4.5 kg N ha⁻¹. Nitrate leaching is the only area in which manure injection exacerbated environmental losses relative to broadcast application. Subtle differences in N₂O emissions were evident, with any liability

### Table 1. Summary of results from all farm simulations.

<table>
<thead>
<tr>
<th>Manure storage</th>
<th>Broadcast</th>
<th>Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily haul†</td>
<td>6 mo</td>
</tr>
<tr>
<td>Side-dress</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Crop yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn silage (t dry matter ha⁻¹)</td>
<td>15.9</td>
<td>15.9</td>
</tr>
<tr>
<td>Corn grain (t dry matter ha⁻¹)</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Crude protein corn silage (%)</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>N side-dress (kg ha⁻¹)</td>
<td>5.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Runoff N (kg ha⁻¹)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>NH₃-N (kg ha⁻¹)</td>
<td>29.6</td>
<td>43.1</td>
</tr>
<tr>
<td>NO₃-N (kg ha⁻¹)</td>
<td>60.4</td>
<td>50.8</td>
</tr>
<tr>
<td>N₂O-N (kg ha⁻¹)</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Total N losses (kg ha⁻¹)</td>
<td>100.1</td>
<td>106.7</td>
</tr>
<tr>
<td>Avg. NO₃ concentration in leachate (ppm)</td>
<td>24.1</td>
<td>20.1</td>
</tr>
<tr>
<td>Reactive N footprint (g N kg⁻¹)</td>
<td>9.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Whole farm NUE§ (%)</td>
<td>38.1</td>
<td>36.4</td>
</tr>
</tbody>
</table>

* Significant treatment differences, one-way ANOVA (P < 0.05).
† Daily haul farm does not have manure storage and is surface applying manure daily.
‡ Total reactive N released to the environment, including secondary sources, per unit of milk produced corrected to 4% fat and 3.3% protein.
§ NUE, nitrogen use efficiency. Total N exported from the farm in useful product over that imported through fertilizer, purchased feed, fixation, and deposition.
associated with manure injection reversed when storage was increased to 12 mo (Table 1).

### Farm Nitrogen Use Efficiency and Profitability

Farm NUE varied from 36 to 44% across the different farming operations (Table 1). For the dairy farm with daily hauling of manure, NUE was in fact intermediate (38%) to the other operations where investments in 6 or 12 mo of storage had been made. The lowest NUE was associated with the farm that broadcast manure and had 6 mo of storage, largely due to the great NH3 losses from the storage and land-applied manure that reduced N availability to the crops. The highest farm NUE was associated with manure injection. To maintain forage quality, all farms that broadcast manure required additional N fertilizer as a side-dress application during the growing season. With manure injection, the side-dressed N fertilizer was no longer required. Expanding manure storage to 12 mo and injecting manure resulted in the greatest farm NUE (44%), largely due to lesser environmental losses as described above.

Transitioning from a dairy farm with no manure storage to one with storage increased net profitability if 6-mo storage was installed but decreased net profitability if a 12-mo storage structure was constructed (Supplemental Table S2). Although environmentally advantageous, 12 mo of storage was not economically beneficial to the small operations we simulated. The average net annual return to management for a farm with 12 or 6 mo of storage was $61,470 and $73,947, respectively. The initial capital costs of 12 mo of storage are difficult to recoup, even over a 25-yr time period. Currently, most farmers in Pennsylvania would not opt to build a 12-mo storage facility without subsidy.

### Conclusions

Whole-farm simulations highlight the importance of including manure injection with manure storage as part of dairy farm development. From the standpoint of N management, transitioning a small farm lacking storage to one with storage involves trade-offs, largely due to the inefficiencies in NUE associated with broadcasting stored manure slurry. Our findings illustrate that the benefits of investing in manure storage are incomplete without the additional use of manure injection to prevent ammonia losses to the environment.

### Acknowledgments

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### References


