Journal of Agricultural and Resource Economics 46(3):380–400 ISSN: 1068-5502 (Print); 2327-8285 (Online)

doi: 10.22004/ag.econ.307457

The Impact of the Clean Water Act on Farm Practices: The Case of U.S. Dairy Concentrated Animal Feeding Operations

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We quantify the impact of the Clean Water Act (CWA) on farm waste management practices of U.S. dairy concentrated animal feeding operations (CAFOs), including storage capacity, land application, and manure removal. We employ a double-hurdle model to examine how dairy farmers adjusted their practices in response to a major policy revision of the CWA in 2003. We find that the revision significantly increased the adoption rate of nutrient management plan (NMP) among dairy CAFOs. The results suggest that the CWA had a heterogeneous and limited impact on dairy CAFOs' waste management practices.

Key words: ARMS data, CAFOs, CWA, double-hurdle model, nutrient management plan, permit, waste management

Introduction

Concentrated animal feeding operations (CAFOs) are animal feeding operations that confine at least a certain number of animals or meet specific pollutant discharging criteria (U.S. Environmental Protection Agency, 2003a).[1] In 2013, there were estimated to be 18,462 CAFOs in the United States (U.S. Environmental Protection Agency, 2013). By 2018, the estimated number had increased by 10%, to 20,382 (U.S. Environmental Protection Agency, 2018). Large CAFOs accounting for only 5% of livestock farms produce 65% of the manure generated in the United States (Gurian-Sherman, 2008). Water pollution by CAFOs has been well documented in recent years (Harden, 2015; Liu et al., 2015; Moses and Tomaselli, 2017). In 2010 about one-third of the wells in Kewaunee County, Wisconsin, did not meet drinking water safety standards. The State of Wisconsin Division of Hearings and Appeals (2012) hypothesized that this contamination was likely generated by local dairy CAFOs. As CAFOs continue to expand across the United States, there is renewed concern about maintaining water quality and protecting public health.

Federal governments have a long history of adopting legislation with the objective of improving water quality (Key and Kaplan, 2007). The Clean Water Act (CWA) became law in 1972 to regulate water pollution from point sources including CAFOs (Copeland, 2011). One important aspect of the CWA is the requirement to purchase permits issued by the National Pollutant Discharge Elimination System (NPDES) program, which is implemented and enforced by the U.S. Environmental Protection Agency (EPA). By purchasing a permit, the farm operator agrees to follow the requirements on management practices specified by the permit. Permit regulation was not,

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Review coordinated by Richard T. Woodward.

[1] Animal feeding operations are operations that confine animals for a more than 45 days in any 12-month period and sustain no grass or other vegetation in the normal growing season (U.S. Environmental Protection Agency, 2003a).

however, strictly enforced until the 2003 revision to the CWA.[2] That revision, which was in full effect by the end of 2006, requires all CAFOs to purchase permits, except for farms that have no potential to discharge pollutants (U.S. Environmental Protection Agency, 2003b). Due to this policy adjustment, CAFO farmers who previously did not own permits were required to purchase permits and fulfill the requirements. One possible response by CAFOs is to change their manure management practices (e.g., by increasing storage capacity, land application of manure, and/or manure removal).

Some qualitative studies on the effectiveness of CWA regulations contain conflicting results. In a study of water pollution in Michigan, Zande (2009) suggests that the CWA is not effective because of the pollutants exempted from regulation. For instance, stormwater run-off from CAFOs is considered "agricultural stormwater discharge" and not regulated by the CWA. A similar criticism has been made by Laitos and Ruckriegle (2013), who indicate that by regulating only point sources, the CWA overlooks the contribution of nonpoint sources to water pollution.[3] Andreen (2004), however, has a favorable view on the effectiveness of the regulations. He argues that the CWA has achieved its designed purpose to reduce industrial pollution. Rechtschaffen (2004) also suggests that water quality has been improved substantially due to the control of point source discharges. None of these studies provide a quantitative assessment of the regulatory impact.

Previous quantitative analyses have tended to focus on regulatory impacts on water quality improvement rather than on the impact on management practices or actions taken in responding to policy change. In an analysis of all major sources of contaminants in southern California from 1971 to 2000, Lyon and Stein (2009) find that the CWA reduced mass emissions of most pollutants by over 65%. Smith and Wolloh (2012) suggest that the water quality of U.S. freshwater lakes as a whole did not improve after the CWA was established, based on their water quality indices. In a more recent study, Keiser and Shapiro (2019) analyze 170,000 monitoring sites and argue that water pollutants have decreased substantially since 1972. They find that the share of water meeting the standards for fishing increased by 12% over the 1972–2001 period.

Individual farms' environmental performance is largely determined by management decisions made by farm owners and operators. Therefore, a better understanding of the regulatory impact on farm management practices is critical for improving the efficacy of policy implementation and for achieving environmental objectives. However, very few studies investigate how the CWA regulations have impacted U.S. livestock operations. Huang, Magleby, and Christensen (2005) undertook an early attempt to analyze the effect of the 2003 CWA revision on the economic well-being of dairy farms in the southwestern United States. They find that for medium and large dairy farms with lagoon systems, the revision decreased net returns by 6%–17%. Their study, however, does not address the adjustment of management practices by farmers in response to the revision. In addition, their results rely on some strong assumptions. For example, the manure application cost of each farm is assumed to be fixed, without accounting for dairy operations' heterogeneity. As the benefits of the CWA depend on its regulatory impact on farm management, a careful empirical analysis is warranted.

In this paper, we analyze how U.S. dairy farms adjusted manure management practices in response to the 2003 CWA revision by employing data from the 2000 and 2010 Agricultural Resource Management Survey (ARMS) of Dairy Costs and Returns Reports. We use the impact of the 2003 revision to infer the overall effectiveness of the CWA regulations on CAFOs' manure management practices, including storage capacity, land application, and manure removal. The results indicate that the 2003 CWA revision significantly increased the adaptation rate of nutrient management plan (NMP) for dairy CAFOs, and CAFOs following management standards of NMPs were on average more likely to have manure storage facilities and to apply manure to land compared with CAFOs that do not comply with NMPs. However, for those who had already implemented these practices, there is no strong evidence of storage and land application adjustments. Further, we

[2] The EPA admitted the ambiguity as to which operations were covered by the regulations in the early period (U.S. Environmental Protection Agency, 2002a).

[3] The water quality issues caused by nonpoint sources are addressed by state-level programs (U.S. Environmental Protection Agency, 2020).

do not find overall significant impact of NMP compliance on manure removal. Finally, no significant changes are found for either participation or implementation level in all management practices for CAFOs that failed to comply with NMPs. Our results suggest a heterogeneous and limited policy impact of the CWA on dairy farm management practices.

To our knowledge, this is the first study to quantify the impact of CWA regulations on the manure management practices of dairy CAFOs. Our study has important implications for related policy design and implementation. Marble (2013) argues that the CWA is considered a "command-and-control" regulation that often causes difficulty in policy enforcement. For instance, administrations with little interest in environmental policy can hinder government oversight. Additionally, command-and-control regulations are not flexible enough to evolve with new scientific knowledge that can improve the policy. He proposes a reflexive policy with market-based incentives to promote environmental protection activities by CAFOs through self-regulation. As limited farm management adjustment is found in our analysis, which can be considered a failure of policy enforcement, the adoption of a reflexive regulation scheme is worth considering.

Background of CAFOs and the CWA

CAFOs fall into three size categories: large, medium, and small. Dairy operations with at least 700 dairy cows are categorized as large CAFOs.[4] Operations with 200–699 cows are defined as medium CAFOs if they meet one of the two discharging criteria: (i) a man-made device transfers manure or wastewater from the operation to surface water or (ii) the animals of the operation contact surface water that runs through the confined area (U.S. Environmental Protection Agency, 2003a). They can also be designated as medium CAFOs by the regulation authority.[5] Operations with fewer than 200 cows can be categorized as small CAFOs only through designation.[6] There are no comprehensive data on the total number of CAFOs or the numbers of specific types of CAFOs, such as dairy (Food & Water Watch, 2015). In 2017, Wisconsin had about 290 dairy CAFOs, all but 10 of which were large CAFOs (phone interview with Thomas S. Bauman, April 18, 2017).

The NPDES program established under the CWA requires CAFOs to purchase NPDES permits, which specify four sets of requirements, including (i) effluent limitations; (ii) special conditions; (iii) standard conditions; and (iv) monitoring, record-keeping, and reporting requirements. Effluent limitations specify the common standards that permit holders must follow under certain conditions. For example, any discharge from the production area is allowed only if dairy farms can handle all manure and process wastewater under extreme rainfall events (e.g., a 25-year, 24-hour rainfall event).[7] Another example is that dry-weather discharges are not permitted. Special conditions are designed to supplement the effluent limitations, accounting for unique conditions of individual operations. Permit holders are required to develop a nutrient management plan (NMP) outlining the management practices designed to reduce CAFOs' impact on water quality. Standard conditions—as well as monitoring, record-keeping, and reporting requirements—include detailed information on the procedures and requirements on how CAFO farmers should keep records of their management

[4] For the more general definition, animal feeding operations with at least 1,000 animal units (AUs) are defined as large CAFOs. Different animal types have different numbers of AUs per unit. For example, the number of AUs for mature dairy cows, horses, and sheep are 1.43, 2, and 0.1, respectively (U.S. Environmental Protection Agency, 2012). See Online Supplement Table S1 for the CAFO thresholds and AUs of major animal types. Note that large CAFOs are defined based on the AU of each individual animal type, not accumulation across types (U.S. Environmental Protection Agency, 2003a). For instance, a farm with 500 mature dairy cows (715 AUs) and 300 horses (600 AUs) is not considered a large CAFO because neither of the individual animal types passes the 1,000-AU threshold, even though the AU sum does.

[5] The regulation authority might designate a farm to be a CAFO if it is considered to be a significant contributor of pollutants, regardless of its size.

[6] Although each state might have its own definition of a CAFO, almost all states follow the federal definitions here (U.S. Environmental Protection Agency, 2002b).

[7] A 25-year, 24-hour rainfall event is defined as "the maximum 24-hour precipitation event with a probable recurrence interval of once in 25 years" (40 CFR § 412.2).

practices and submit reports to the permit authority (U.S. Environmental Protection Agency, 2003a).[8]

NMPs address the management practices associated with storage facilities, land application, and documentation (Koelsch, 2005). CAFO farmers are expected to meet the minimum standards to reduce their impact on water quality while achieving their production goals. They are also responsible for updating their NMPs to reflect the current situation of their operations. The successful implementation of NMPs is thought to reduce the environmental damage caused by CAFOs, which is important for the effectiveness of CWA regulations (Centner, 2004; Sims et al., 2005). In 2010, 77% of dairy farms in our sample implemented nutrient management plans.

There is anecdotal evidence that dairy farmers have adjusted their management practices in response to regulatory changes (phone interview with Thomas S. Bauman, April 18, 2017). Increasing storage capacity, land application, and manure removal from the operation are considered the most common ways for Wisconsin farmers to respond to CWA regulations. Additionally, some farmers are reluctant to expand their farms to the extent that passes the large CAFO threshold to avoid complying with permit requirements (interview with B.L. Jones, April 25, 2017).

Empirical Strategy

We identify the effect of the CWA by comparing CAFOs' farm management practices in 2000 with those in 2010, given that the CWA becomes more stringent after 2006 (when the 2003 revision came into effect) such that all CAFOs are now required to purchase permits. Another potential approach is to compare the management practices of CAFOs and non-CAFOs in 2010. This latter method has a serious shortcoming because CAFOs are generally larger. Given that the management practices of large and small dairy operations are fundamentally different in many aspects that cannot be fully accounted for by controlling only for farm size, the direct comparison between CAFOs and non-CAFOs is inadequate to identify the regulatory impact. Therefore, we employ the approach discussed above to identify the policy impact.

As we seek to identify the impact of the CWA by comparing CAFOs' management practices in 2000 (pre-revision) and 2010 (post-revision), the identification strategy requires that there is no other federal-level policy change or implementation affecting CAFOs' practices over the sample period. Otherwise, the difference in management practices between the two periods might be wrongly attributed to the CWA, while it is in fact caused by other policies. The first challenge to this assumption is the 2008 CWA revision that allows CAFO farmers to voluntarily self-certify compliance with the permit rule, which may potentially weaken the CWA. However, the EPA estimated that the number of CAFOs expected to seek permit coverage went down by only 200, from 15,500 under the 2003 revision to 15,300 in 2008 (Copeland, 2011). Therefore, the 2008 revision is unlikely to affect our identification. The other challenge is the promotion of anaerobic (methane) digesters for farm uses by the EPA and USDA over the 2000–2010 period, which can change CAFOs' manure management practices (Lazarus, 2008; Di Camillo, 2011). This could potentially confound our estimate of the policy impact. However, only 2 out of 2,758 farms in our sample are reported to have anaerobic digesters.[9] As such, the government's support of the use of anaerobic digesters does not affect our identification.

In addition to federal-level policies, the policy impact of the CWA could be obscured by the effects of state-level environmental policies, which have separate and—in some cases—more stringent requirements than the federal NPDES permits. As each state has its own policy regulating the management practices of dairy CAFOs, it is hard to verify all the details for all states (Norwood, Luter, and Massey, 2005). However, many states have explicit statutory language prohibiting state-level regulations to be more stringent than federal regulations. Table S2 in the Online Supplement (see www.jareonline.org) summarizes the statutes with stringency prohibition language for all states

[8] See the Online Supplement for the details of NPDES permit requirements.
[9] We estimate the model excluding these two farms and obtain nearly identical results.

with at least ten CAFOs in our sample. These states account for 86% of the sampled CAFOs. Of these states, four out of nine have stringent prohibition language in their statutes. Another two states, Florida and Texas, allow stricter state-level policy only under strong conditions. Therefore, most of the major states are not expected to have regulations more stringent than the CWA. This reduces the concern for our identification of the policy impact. California, New Mexico, and Washington do not have stringent prohibition language.

The most prominent water quality regulation in California before 2000 is the Porter–Cologne Act, implemented in 1969. The policy establishes two agencies, the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Boards (RWQCBs), to regulate statewide water quality. The RWQCBs, overseen by the SWRCB, enforce the NPDES permit requirements (California State Water Resources Control Board, 2014). The Porter–Cologne Act outlines the state-specific requirements and incorporates the regulations of the CWA after its enactment in 1972 (Jones et al., 2003). Therefore, it is unclear whether the Porter–Cologne Act is more stringent than the CWA. Despite this potential confounding factor, the identification is supported by the fact that CAFOs in California are subject to the special requirements of the NPDES permits from the CWA on waste discharges to surface waters (Attwater and Markle, 1988). As CAFOs tend to discharge pollutants to surface waters (Innes, 2000), the management practices of California CAFOs should be affected by the CWA. Therefore, we expect to at least partially identify the regulatory impact of the CWA on CAFOs in California if the impact exists.

The most important water quality law in New Mexico is the Water Quality Act (WQA) (State of New Mexico Interstate Stream Commission, 2016), adopted in 1967. The WQA establishes the Water Quality Control Commission as the main authority for water quality management in the state. Despite the potential existence of more stringent policy, there is evidence that regulations in New Mexico are strongly influenced by the federal policy, given the following two facts: First, the WQA was created with an intent to implement water quality standards consistent with the CWA (Leavitt, 2006; New Mexico Environment Department, 2020). Second, New Mexico has no delegated authority for a state NPDES program (U.S. Environmental Protection Agency, 2016). That is, the EPA directly administers the NPDES program in the state. Because of the close tie between federal- and state-level regulations, CAFOs in New Mexico are expected to be affected by the CWA, which supports our identification of the policy impact.

The Washington State Department of Ecology (2006) enacted several state-level water laws to protect water quality in Washington.[10] These regulations include requirements that differ from those in the CWA. As such, CAFOs in Washington state might be regulated under more stringent policies compared to the CWA. However, Washington CAFOs are still expected to be affected by the CWA for the following reasons: First, the Washington State Department of Ecology (WSDE) still issues NDPES permits under the CWA for CAFO farmers. In addition, the State Waste Discharge Permit program, the other permit program implemented by the WSDE, is based on the federal effluent limitation guideline from the NDPES program (Washington State Department of Ecology, 2019). Therefore, the impact of the CWA on CAFOs in Washington state can still be partially identified.

Because of the ambiguity as to whether we can identify the impact of the CWA on CAFOs in New Mexico and Washington, we conduct a robustness check using the subsample without farms in the two states in a latter section. The results are similar to the main results based on the full sample.

The above discussion of the federal- and state-level regulations suggests that (i) we do not expect other federal-level policy changes that can substantially affect manure management practices over the 2000–2010 period;[11] (ii) most of the major states in our sample are not expected to have

[10] Some of the major laws include the Water Code of 1917, 1945 Groundwater Code, 1998 Watershed Planning Act, Water Resources Act of 1971, and Growth Management Act (Washington State Department of Ecology, 2006).

[11] In the regression analysis that follows, we include farm-level financial related variables such as farm assets and farm debts to control for the potential confounding impact of macroeconomic events such as the Great Recession of 2008. Because of data limitations, we are not able to fully control some other potentially influencing factors such as changing in political power over the sample period. But we believe the related direct impact is not substantial and does not significantly affect the identification. We thank a reviewer for pointing this out.

regulations more stringent than the CWA; and (iii) states that might have more stringent policy are still affected by CWA regulations. Therefore, our empirical strategy should be able to correctly identify the policy impact of the CWA.

Survey Data and Descriptive Analysis

For this analysis, we construct a pooled cross-sectional dataset from the Agricultural Resource Management Survey (ARMS) of Dairy Costs and Returns Reports for 2000 and 2010.[12] The data contain comprehensive information on costs, revenue, production and marketing practices, and manure management of dairy farms in the major dairy-producing states (22 in the 2000 survey and 26 in 2010).[13] The 2000 and 2010 surveys are comparable because the USDA's National Agricultural Statistics Service (NASS) and Economic Research Service (ERS) collect the two surveys using similar approaches with a nationally representative sample (Gillespie et al., 2010). A number of studies support the use of the ARMS as a series of independent cross-sectional data for econometric analysis (see, e.g., Gillespie et al., 2010; Khanal, Gillespie, and MacDonald, 2010; Williamson, 2011; Featherstone, Park, and Weber, 2012; U.S. Department of Agriculture, 2018; Holly et al., 2019).

We categorize manure management practices by three characteristics: (i) manure storage capacity, (ii) total acres of land with manure application, and (iii) percentage of manure removed from the operation. The "manure storage capacity" is calculated by the sum of the capacity of each storage facility reported in the survey. The variable "total acres of land application" is the sum of the total acres of land, pastureland, and hay reported to be applied with manure. The "percentage of manure removal" includes the dairy manure that is sold, hauled off for a fee, or given away. All of them are expected to be affected by the CWA regulations based on requirements from effluent limitations and NMPs as well as anecdotal evidence (U.S. Environmental Protection Agency, 2004; Nennich et al., 2005, phone interview with Thomas S. Bauman, April 18, 2017). The ARMS data provide sampling weights determined by the selection probability of dairy farms, so that the sample allocation is representative of the population at the state level (Ebel and Vasavada, 2010). Our sample includes 865 and 1,893 dairy farms in the 2000 and 2010 surveys, respectively.[14] Table 1 reports the estimated population averages, standard deviations, and medians of the three management practice variables and farm sizes using ARMS sampling weights.[15] It is worth noting that the average storage capacity over the sample period increased from 8,205,500 gallons in 2000 to 37,621,300 gallons in 2010 after applying the ARMS sampling weights.[16] The significant increase is mainly driven by higher participation rate and a small proportion of farms with significant storage capacity in 2010. As shown in Table 2, the percentage of CAFOs with 0 storage capacity decreased from 13% in 2000 to 7% in 2010. If we exclude farms with storage capacity of 0 or above the 95th percentile, the average storage capacity would only increase from 451,257 to 726,803 gallons over the sample period.[17] We observe the similar patterns for the per cow storage capacity. The large standard deviations of the variables indicate significant heterogeneity among dairy operations in both years.

[12] We do not construct a panel dataset because only small numbers of farms are sampled in both years. The challenge of constructing the panel data from the ARMS is often discussed in the literature (see, e.g., National Research Council, 2008; Featherstone, Park, and Weber, 2012).

[13] The following states are included in both surveys: AZ, CA, FL, GA, ID, IL, IN, IA, KY, MI, MN, MS, NM, NY, OH, PA, TN, TX, VT, VA, WA, and WI. States included in only the 2010 survey are CO, KS, ME, and OR.

[14] We dropped observations with missing values in the three management practices, which are about 1% of the original data. This is expected to have minimal impact on the analysis. Also, the dropped observations appear to be randomly distributed in terms of management practices and farm size.

[15] See Online Supplement Table S3 for the sample statistics without applying the sampling weights.

[16] We see significant increases in storage capacity for both CAFOs and non-CAFOs over the sample period. As reported in Table 3, the average capacity of CAFOs increased from about 8.8 million gallons in 2000 to over 46 million gallons in 2010. The average capacity of non-CAFOs changed from approximately 0.6 million to 1.8 million gallons over the same period. All numbers are calculated with the ARMS sampling weights. We thank a reviewer for pointing this out.

[17] We conduct a robustness check for the subsample excluding farms with 0 storage capacity or storage capacity above the 95th percentile. The results are consistent with our main finding.

Table 1. Summary Statistics of Management Practices in 2000 and 2010 for All Farms

Management Practice	Units	2000	2010
Storage capacity	1,000 gallons		
Mean		820.55	3762.13
Std. dev.		140.41	647.32
Median		5.00	100.00
Land application	Acres		
Mean		112.80	155.62
Std. dev.		5.28	6.62
Median		75.00	93.00
Manure removal	%		
Mean		3.91	6.09
Std. dev.		0.58	0.89
Median		0.00	0.00
Storage capacity per cow	1,000 gallons/head		
Mean		4.58	8.58
Std. dev.		0.74	0.98
Median		0.97	2.78
Land application per cow	Acres/head		
Mean		1.53	1.52
Std. Dev.		0.05	0.05
Median		0.95	1.11
Farm size	Head		
Mean		109.84	174.52
Std. Dev.		7.41	9.14
Median		58.00	66.00
No. of obs.		865	1,893

Notes: These statistics are estimated using sampling weights provided by the ARMS data. See Online Supplement Table S3 for the sample statistics without applying sampling weights.

Despite the rich information in our data, there is no variable available in the survey to identify CAFOs. Therefore, we define CAFOs in this analysis as farms with at least 700 cows because most U.S. CAFOs are classified as large CAFOs, with no fewer than 700 cows. There are 52 and 150 CAFOs in the 2000 and 2010 surveys, respectively. Table 2 reports summary statistics, including the number of CAFOs and non-CAFOs in each state, the percentage of CAFOs with NMP, and CAFO participation rates for each management practice for both surveys. It shows that there is a significant increase in use of nutrient management plans in 2010. In addition, there are many observations with 0 values for the management practice variables. These are not missing values and reflect actual numbers reported by farmers.[18]

One simplified method to identify the impact of CWA regulations on dairy CAFOs is to determine whether there are any changes in the relationship between manure management practices and farm size measured by the number of cows. If there are marked changes in management practices when farm size is right above the threshold, 700 cows for large CAFOs, the permit regulation might have a significant impact on farm practices. Figure 1 shows the per cow storage capacity, per cow land application, and percentage of manure removal by farm size for all sampled farms in 2010.[19]

[18] A blank answer (missing value) is shown as a period in the dataset and a 0 value is shown as 0.

[19] We focus on the 2010 sample here because these dairy farms operated under the more stringent regulations after the 2003 revision and therefore are most likely to be affected. Note that percentage of manure removal is not based on manure removal per cow because it is a percentage measurement.

Table 2. Numbers of CAFOs and Non-CAFOs in the Sample States, Percentage of CAFOs in Compliance with NMP, and Participation of Management Practices

	2000		2010	
State	**CAFO**	**Non-CAFO**	**CAFO**	**Non-CAFO**
Arizona	4	3	19	2
California	10	41	39	37
Colorado	0	0	10	18
Florida	6	16	10	21
Georgia	1	37	1	49
Idaho	5	26	20	47
Illinois	0	34	0	51
Indiana	0	30	2	87
Iowa	0	20	2	74
Kansas	0	0	3	39
Kentucky	0	58	0	56
Maine	0	0	0	45
Michigan	0	19	3	66
Minnesota	0	55	1	85
Missouri	0	22	0	63
New Mexico	14	6	4	2
New York	2	57	4	125
Ohio	0	32	2	98
Oregon	0	0	5	55
Pennsylvania	0	57	1	126
Tennessee	0	41	0	63
Texas	6	49	6	50
Vermont	0	37	1	123
Virginia	0	36	0	76
Washington	3	16	8	49
Wisconsin	1	121	9	236
Total	52	813	150	1,743
Percentage of CAFOs				
in compliance with NMPs	50%		77%	
with 0 storage capacity	13%		7%	
with 0 land application	33%		25%	
with 0 manure removal	42%		47%	

The figure suggests that there are no distinctive changes close to the threshold for all management practices.

We also examine the regulatory impact using the summary statistics of the management practices. Table 3 shows the estimated mean, standard deviation, and median of individual management practices for CAFOs in 2000 and 2010 after applying the ARMS sampling weights.[20] Applying the adjusted Wald test for mean equality, we find that the means of total and per cow storage capacities as well as total acres of land application are significantly higher in 2010 than those of 2000 at the 5% significance level (see Table 4).[21] This suggests that the CWA may affect the management practices of dairy CAFOs. The descriptive evidence, however, does not account

[20] See Online Supplement Table S4 for the summary statistics of CAFOs without incorporating sampling weights.

[21] We also test the mean equality for the sample statistics without applying the sampling weights using Welch's t-test. The results are similar except that the land application is no longer significantly lower in 2000 than 2010. See Online Supplement Table S5 for the results.

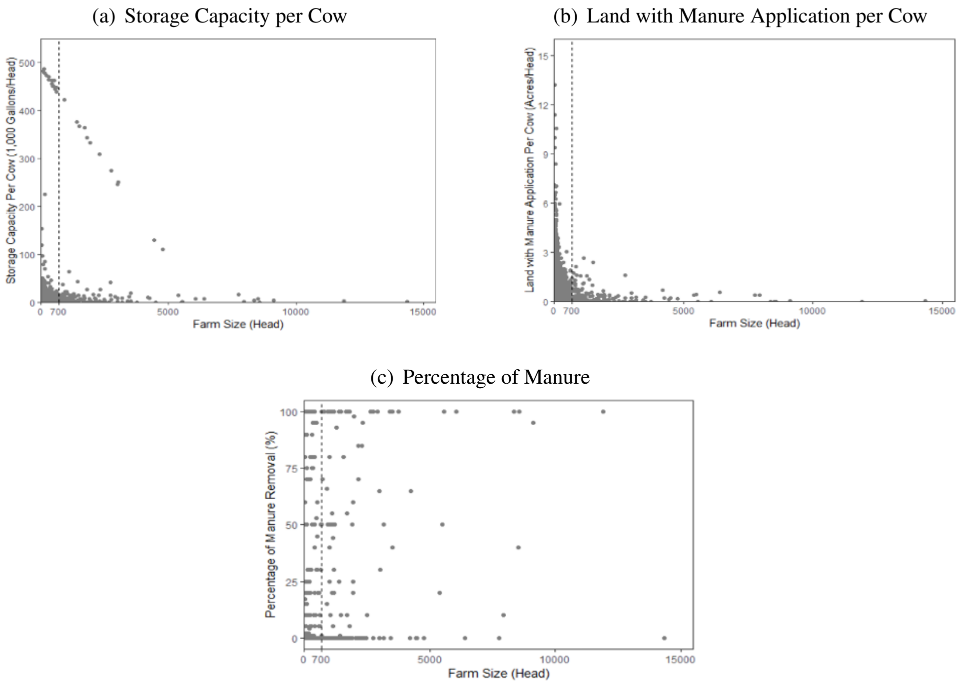

Figure 1. Storage Capacity per Cow, Land with Manure Application per Cow, and Storage Capacity by Farm Herd Size for CAFOs in 2010

Notes: Dashed lines indicate the threshold of large CAFOs (700 cows). We also include the log transformation of data to better examine the pattern of small values in Online Supplement Figure S1. Similarly, we do not see distinctive changes in management practices around the CAFO threshold.

for farmers' decision-making processes or control for other influencing factors related to farm management.

Empirical Analysis

To address these issues, we employ a double-hurdle framework (Cragg, 1971) to model farmers' decisions with respect to management practices. In our model, CAFO farmers first choose whether to engage in a certain manure management practice and then decide the level of implementation. This two-stage decision approach is motivated by the large number of zeros in the sample, indicating that many CAFOs did not have any storage capacity, apply manure to land, or remove manure from the operation at all.[22] Other popular methods of dealing with 0 observations include Tobit and Heckman selection models (Tobin, 1958; Blundell and Meghir, 1987; Puhani, 2000). The double-hurdle model, however, is more appropriate for the following reasons. First, the zeros in management practices are expected to reflect nonparticipations that can be effectively captured by the double-hurdle model (Newman, Henchion, and Matthews, 2003). The Tobit model, on the other hand, is appropriate for modeling the censored data, which is fundamentally different than modeling the two-stage decision in this analysis. Second, unlike the standard Tobit model, the double-hurdle model has a more general likelihood function that allows the decisions on participation and level of implementation to be determined by different processes (Jones, 1989). Therefore, the impacts of the same covariate in two stages can have different signs (García, 2013). This is important for our analysis because farm characteristics can affect the two types of decisions differently. For example,

[22] The percentage of farms with 0 storage capacity, land application, and manure removal in our sample is 24%, 7%, and 88%, respectively.

Table 3. Summary Statistics of CAFO Management Practices, 2000 and 2010

Management Practice	Units	2000	2010
Storage capacity	1,000 gallons		
Mean		8,826.97	46,268.98
Std. dev.		1,601.32	11,383.97
Median		6,000.00	6,856.49
Land application	Acres		
Mean		263.22	636.88
Std. dev.		66.91	82.05
Median		200	326
Manure removal	%		
Mean		41.75	27.52
Std. dev.		10	3.96
Median		50	0
Storage capacity per cow	1,000 gallons/head		
Mean		8.31	25.57
Std. dev.		1.39	6.24
Median		4.99	5.27
Land application per cow	Acres/head		
Mean		0.28	0.48
Std. Dev.		0.08	0.07
Median		0.2	0.25
Farm size	Head		
Mean		1,102.28	1,714.25
Std. Dev.		75.92	122.47
Median		930	1,150
No. of obs.		52	150

Notes: These statistics are estimated using sampling weights provided by the ARMS data. See Online Supplement Table S4 for the sample statistics without applying sampling weights. Summary statistics of the other explanatory variables are included in Online Supplement Table S7.

Table 4. *F*-Statistics of the Adjusted Wald Test for Equality in Estimated Population Means for Management Practice Variables between 2000 and 2010 (*N* = 202)

Management Practice Variables	*F*-Statistics
Storage capacity	10.61***
Land application	12.46***
Manure removal	1.75
Storage capacity per cow	7.30***
Land application per cow	3.46*

Notes: Single and triple asterisks (*, ***) denote significance at the 10% and 1% levels, respectively.

having more labor might decrease the probability that a farm participates in land application because alternative options, such as removing manure from the operation or manure storing, are more feasible. However, if land application is already implemented, more labor can boost the total acres of land with manure application as more people can engage in the activity. Third, compared with the Heckman selection model, the double-hurdle model is more robust against multicollinearity when the first- and second-stage equations have many variables in common (Leung and Yu, 1996; Madden, 2008). As the decisions on participation and level of implementation are often affected by some common factors, the double-hurdle model is more appropriate than the Heckman selection model. Some recent applications of the double-hurdle model for farmers' decisions on technology adoption include those by Ricker-Gilbert, Jayne, and Chirwa (2011), Beshir et al. (2012), and Tambo and Abdoulaye (2012).

For the management practice k, the first-stage decision is specified in the following probit equation:

$$(1) \qquad w_{ki} = \alpha_k + \alpha_k^{10} I_i^{10} + \boldsymbol{X}_{\boldsymbol{i}}^{\prime} \boldsymbol{\beta}_{\boldsymbol{ki}} + \sum_s \rho_{ks} D_{si} + \delta_k CAFO_i + \delta_k^{10} I_i^{10} CAFO_i + \varepsilon_{ki}$$

$$(2) \qquad = \boldsymbol{Z}_i^{\prime} \boldsymbol{\gamma}_k + \varepsilon_{ki}, \; k = 1,2,3,$$

where w_{1i}, w_{2i}, and w_{3i} are the selection variables describing a farmer's decisions to, respectively, build manure storage on the farm, apply manure on the farm's own land, and remove manure from the operation for farm i. D_{si} is a dummy variable indicating the location of farm i in state s.[23] The vector $\boldsymbol{X_i}$ includes farm characteristics such as total land acres, total farm assets, total debts, and weekly labor hours of the farm.[24] $CAFO_i$ indicates the CAFO status of farm i (i.e., whether it has at least 700 cows), I_i^{10} is the indicator for 2010, ε_{ki} is the normally distributed error term with 0 mean, and $\boldsymbol{\gamma}_k$ is the vector of parameters associated with $\boldsymbol{Z}_i$, the vector of all explanatory variables including the intercept in equation (1).

In the second stage, farmers decide the level of implementation of the management practices:[25]

$$(3) \qquad y_{ki}^{*} = \exp\left(\bar{\alpha}_k + \bar{\alpha}_k^{10} I_i^{10} + \boldsymbol{X}_{\boldsymbol{i}}^{\prime} \bar{\boldsymbol{\beta}}_{\boldsymbol{ki}} + \sum_s \bar{\rho}_{ks} D_{si} + \bar{\delta}_k CAFO_i + \bar{\delta}_k^{10} I_i^{10} CAFO_i + v_{ki}\right)$$

$$(4) \qquad = \exp\left(\boldsymbol{Z}_i^{\prime} \boldsymbol{\lambda}_k + v_{ki}\right)$$

and

$$(5) \qquad y_{ki} = \begin{cases} y_{ki}^{*} \text{ if } w_{ki} > 0 \\ 0 \text{ otherwise} \end{cases}, \; k = 1,2,3,$$

where y_{1i}, y_{2i}, and y_{3i} are, respectively, per cow storage capacity, per cow acres of land with manure application, and percentage of manure removal for farm i. We use per cow and percentage measures of the management practices as the practices are expected to be simultaneously determined with the farm size.[26] y_{ki}^{*} is the associated latent variable; if w_{ki} is less than 0, the farmer does not implement management practice k (i.e., $y_{ki} = 0$). v_{ki} is the error term with 0 mean, and $\boldsymbol{\lambda}_k$ is the vector of

[23] There are 22 and 26 states in the 2000 and 2010 data, respectively. We include state-level dummies to control the difference in management practices across states induced by factors we do not observe such as weather, agricultural traditions, and non-CAFO-related policies. See Online Supplement Table S6 for the summary statistics of management practices in each state.

[24] See Online Supplement Table S7 for the summary statistics of farm characteristics. Total farm assets and total debts are converted to the real dollar values using the Consumer Price Index with 2000 as the base year. Farm profitability as represented by net farm income is another farm characteristic that could be included. We do not include it because approximately 14% of the CAFOs in our sample have missing values for this variable.

[25] We use an exponential form because it provides a percentage interpretation for the impact on management practices.

[26] We do not include farm size as an explanatory variable because it is potentially endogenous and could bias the estimates.

parameters associated with $\boldsymbol{Z}_i$.[27] We obtain the parameter estimates of $\boldsymbol{\theta_k} = (\boldsymbol{\gamma}_k, \boldsymbol{\lambda}_k)$ by choosing $\boldsymbol{\theta_k}$ to maximize the log-likelihood function:

$$\begin{aligned}\log L_k = &\sum_{i=1}^{n} I(y_{ki} - 0)\log\Phi(-\boldsymbol{Z}_i'\boldsymbol{\gamma}_k) + \sum_{i=1}^{n} I(y_{ki} > 0)\log[1 - \Phi(-\boldsymbol{Z}_i'\boldsymbol{\gamma}_k)] \\ &+ \sum_{i=1}^{n} I(y_{ki} > 0)\left\{\log\phi\left[\frac{\log(y_{ki}) - \boldsymbol{Z}_i'\boldsymbol{\lambda}_k}{\sigma_{ki}}\right] - \log(\sigma_{ki}) - \log(y_{ki})\right\},\ k = 1,2,3,\end{aligned} \tag{6}$$

where Φ and ϕ denote the cumulative distribution (CDF) and the probability density (PDF) of the standard normal distribution, respectively. σ_{ki} is the heteroskedastic standard error and n is the number of observations. $I(\cdot)$ is the indicator function equal to 1 if $y_{ki} > 0$, and 0 otherwise. We can view the likelihood function as a composition of three components for the two-stage decision process. The first component, $\sum_{i=1}^{n} I(y_{ki} = 0)\log\Phi(-\boldsymbol{Z}_i'\boldsymbol{\gamma}_k)$, represents the likelihood for operations that do not participate in the k manure management practice. The second component, $\sum_{i=1}^{n} I(y_{ki} > 0)\{\log[1 - \Phi(-\boldsymbol{Z}_i'\boldsymbol{\gamma}_k)]\}$, is the likelihood for operations that engage in the k management practice with $y_{ki} > 0$. The last component, $\sum_{i=1}^{n}\{I(y_{ki} > 0)\log\{\phi[\{\log(y_{ki}) - \boldsymbol{Z}_i'\boldsymbol{\lambda}_k/\sigma_{ki}]\} - \log(\sigma_{ki}) - \log(y_{ki})\}$, captures the likelihood of farms implementing the manure management practice k at the level of y_{ki}.

The focus here is to estimate δ_k^{10} in equation (1) and $\bar{\delta}_k^{10}$ in equation (3) ($k = 1,2,3$), which are the coefficients on the interaction terms of the 2010 indicator and the CAFO status in the two stages quantifying the effects of the CWA regulations on CAFOs' management practices in 2010 compared to those in 2000. For the first stage specified in equation (1), if the estimates of δ_k^{10}s are found to be positive and significantly different from 0, CAFOs are more likely to have manure storage, to adopt manure land spreading, or to remove manure from the operation after the 2003 revision, *ceteris paribus*. For $\bar{\delta}_k^{10}$ in the second stage, a significant and positive estimate indicates that on average more stringent policy revision pushes up CAFO per cow storage capacity, per cow land application, or manure removal, *ceteris paribus*. Such results would provide evidence that the CWA has significantly impacted dairy CAFO manure management practices.

Table 5 reports the estimation results. We find that CAFOs' farm management practices in 2010 are not significantly different from those in 2000 at the 5% significance level. This indicates a limited impact of the CWA regulations on farm management practices of dairy CAFOs at the aggregate level. This result is supported by the graphical analysis in the previous section, where we see no apparent difference in the three practice variables between CAFOs and non-CAFOs with similar farm sizes in 2010.

To explore the potential heterogeneity of policy impact, we include two additional interaction terms to distinguish the impacts between CAFOs with and without NMP compliance. Specifically, the first- and second-stage equations are specified as

$$\begin{aligned} w_{ki} = &\tilde{a}_k + \tilde{a}_k^{10} I_i^{10} + \boldsymbol{X}_i'\tilde{\boldsymbol{\beta}}_{ki} + \sum_s \tilde{\rho}_{ks} D_{si} + \tilde{\delta}_k CAFO_i \\ &+ \tilde{\lambda}_k CAFO_i NMP_i + \tilde{\lambda}_k^{10} I_i^{10} CAFO_i NMP_i + \varepsilon_{ki},\ k = 1,\ 2,\ 3,\end{aligned} \tag{7}$$

$$\begin{aligned} y_{ki}^* = &\exp(\bar{\tilde{\alpha}}_k + \bar{\tilde{\alpha}}_k^{10} I_i^{10} + \boldsymbol{X}_i'\bar{\tilde{\boldsymbol{\beta}}}_{ki} + \sum_s \bar{\tilde{\rho}}_{ks} D_{si} + \bar{\tilde{\delta}}_k CAFO_i + \bar{\tilde{\delta}}_k^{10} I_i^{10} CAFO_i \\ &+ \bar{\tilde{\lambda}}_k CAFO_i NMP_i + \bar{\tilde{\lambda}}_k^{10} I_i^{10} CAFO_i NMP_i + v_{ki}),\ k = 1,\ 2,3,\end{aligned} \tag{8}$$

[27] Note that the errors in two stages, ε_{ki} and v_{ki}, are independent. This independent covariance structure has the advantage of avoiding spurious dependency using a correlated structure (Smith, 2003).

Table 5. Regression Results of the Overall Effect of the CWA on Management Practices (N = 2,758)

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
Stage I (participation)							
CAFO		0.130	0.308	−0.050	0.286	0.346	0.336
CAFO × 2010		0.054	0.412	−0.142	0.252	0.194	0.355
Total land	Acres/head	−0.018*	0.010	−0.107***	0.031	−0.189***	0.041
Total debt	$1,000/head	0.059***	0.011	0.001	0.022	0.004	0.020
Total asset value	$1,000/head	0.011***	0.003	$3.00E-05$	0.007	0.002	0.007
Labor hours	Hours/week/head	−0.120***	0.041	−0.082*	0.046	−0.006	0.034
Year 2010		0.416***	0.086	0.322***	0.107	−0.281**	0.135
Intercept		1.732***	0.216	1.030***	0.192	−0.236	0.303
Stage II (level)							
CAFO		−0.234	0.390	−0.336	0.214	0.004	0.180
CAFO × 2010		0.617*	0.368	−0.257	0.221	0.143	0.220
Total land	Acres/head	−0.024*	0.014	0.028***	0.006	−0.160**	0.064
Total debt	$1,000/head	0.040**	0.019	−0.004	0.005	0.029	0.025
Total asset value	$1,000/head	0.001	0.005	0.007***	0.002	0.030**	0.012
Labor hours	Hours/week/head	−0.057**	0.028	0.034**	0.015	0.100	0.067
Year 2010		0.085	0.118	0.047	0.047	−0.369*	0.194
Intercept		8.417***	0.303	0.244	0.244	3.853***	0.251
Likelihood ratio test statistic		766***		1,773***		696***	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" refers to the dummy variable of 2010. Likelihood ratio test statistics are calculated against the intercept-only model. Standard errors are clustered at the state level. State dummies are included. Single, double, and triple asterisks (*, **, ***) denote significance at the 10%, 5%, and 1% levels, respectively.

where NMP_i is an indicator equal to 1 if farm i adopts the NMP management standard and 0 otherwise. $\tilde{\lambda}_k$, $\bar{\bar{\lambda}}_k$, $\tilde{\lambda}_k^{10}$, and $\bar{\bar{\lambda}}_k^{10}$ are parameters of interest. A positive and statistically significant value of $\tilde{\lambda}_k$ (or $\tilde{\lambda}_k + \tilde{\lambda}_k^{10}$) indicates that complying with NMPs increases the probability of participating management practice k for CAFOs in 2000 (or 2010). If the estimated coefficient $\bar{\bar{\lambda}}_k$ (or $\bar{\bar{\lambda}}_k + \bar{\bar{\lambda}}_k^{10}$) is positive and statistically significant, NMP compliance increases the level of implementation of practice k in 2000 (or 2010).[28]

Analyzing whether NMP compliance affects CAFOs' management practices enables us to identify the heterogeneous impact of the policy impact. The CWA requires CAFOs to develop and implement NMPs through the NPDES permit program, which was not strictly enforced until the 2003 revision (U.S. Environmental Protection Agency, 2002a, 2003a). Both descriptive evidence and regression analysis suggest that the 2003 CWA revision increases CAFOs' NMP compliance. The percentage of CAFOs that comply with NMPs increased from 50% to 77% over the sample period of 2000–2010.[29] As the 2003 CWA revision pushes up NMP compliance rates, significant differences in management practices between compliant and noncompliant CAFOs would indicate the overall effectiveness of the CWA.

Table 6 reports the estimation results of equations (7) and (8). Table 7 further summarizes policy impacts corresponding to NMP compliance status, which is the focus of our discussion here. We find that CAFOs in compliance with NMPs are on average more likely to implement manure storage and land application of manure in both 2000 and 2010 than those without NMPs. The significantly positive coefficients on CAFO × NMP suggest strong evidence for a positive impact of the NMP compliance on manure storage and land application for CAFOs in 2000, and this impact remains strong in 2010. Nonetheless, for CAFO farmers already participating in these two practices, we do not find significant changes in the level of implementation (e.g., capacity of manure storage or acres of land with manure application). In addition, there is no evidence of changes in manure removal due to NMP compliance. While CAFOs in compliance with NMPs are more likely to remove manure off-farm in 2000, we do not see this tendency in 2010 as the NMP impact in 2010 is not significantly different from 0.

While the coefficient estimates help us understand whether NMP compliance has impact on management practices, they do not directly translate into the marginal impact of NMP compliance on management practices. Therefore, we further quantify the overall impact of NMP compliance by computing its average marginal impact on participation rates of management practices, which measures the average percentage increases in the participation rates of management practices under the counterfactual scenario, where noncompliant CAFOs adopt NMP management standard. The details are as follows: First, we calculate the conditional probability of participating the management practice for all sample CAFOs in both 2000 and 2010 given that they do not comply with an NMP (i.e., the variable $NMP = 0$). Second, we calculate the probability given that they adopt an NMP (i.e., $NMP = 1$). Finally, we compute the difference between two probabilities for each observation and take the average as the average marginal impact of NMP on participation rate. The results are shown in the last row of Table 7. We see that adopting management standards of NMP increases the probability of implementing manure storage and land application for CAFOs by 15.7% and 24.5%, respectively. The average marginal impact on the participation rate of manure removal is small and statistically insignificant. The results support our finding that CAFOs in compliance with NMPs are more likely to implement manure storage and to apply manure to land.

Finally, the insignificant coefficients on the variable CAFO × 2010 (in Table 6) indicate that there is no strong evidence of management practice adjustment for noncompliant CAFOs after the 2003 revision. This is consistent with the results in Table 5, where we do not see strong evidence that CAFOs' management practices in 2010 are different from those in 2000 at the aggregate level.

[28] Note that the coefficients themselves do not have direct interpretations on marginal effects. See Table 7 for the marginal effects and related discussion below.

[29] The related regression results are reported in Online Supplement Table S8.

Table 6. Regression Results of the Effect of the NMP Compliance on Management Practices (*N*=2,758)

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
Stage I (participation)							
CAFO		−0.388	0.317	−0.693*	0.392	0.684	0.446
CAFO × 2010		−0.102	0.546	−0.004	0.275	−0.428	0.523
CAFO × NMP		1.309**	0.622	1.588***	0.443	−0.622***	0.235
CAFO × 2010 × NMP		−0.375	0.579	−0.945*	0.553	0.967***	0.335
Total land	Acres/head	−0.017*	0.010	0.108***	0.032	−0.189***	0.041
Total debt	$1,000/head	0.058***	0.011	−0.005	0.021	0.003	0.020
Total asset value	$1,000/head	−0.011***	0.003	−0.0003	0.007	0.002	0.007
Labor hours	Hours/week/head	−0.120***	0.041	−0.081*	0.045	−0.008	0.034
Year 2010		0.418***	0.086	0.324***	0.106	−0.283**	0.135
Intercept		1.725***	0.219	1.024***	0.195	−0.238	0.302
Stage II (level)							
CAFO × 2010		0.182	0.499	−0.201	0.199	0.097	0.247
CAFO × NMP		0.488	0.763	−0.486*	0.258	0.275	0.356
CAFO × 2010 × NMP		−0.706	0.786	−0.185	0.337	−0.228	0.319
CAFO × 2010		0.370	0.925	0.295	0.478	−0.051	0.387
Total land	Acres/head	−0.024*	0.013	0.028***	0.006	−0.159**	0.064
Total debt	$1,000/head	0.041**	0.019	−0.005	0.006	0.032	0.026
Total asset value	$1,000/head	0.001	0.005	0.007***	0.002	0.030***	0.012
Labor hours	Hours/week/head	−0.058**	0.028	0.034**	0.015	0.098	0.068
Year 2010		0.084	0.117	0.063	0.047	−0.374*	0.195
Intercept		8.421***	0.301	0.067	0.244	3.867***	0.251
Likelihood ratio test statistic		780***		1,792***		701***	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Likelihood ratio test statistics are calculated against the intercept-only model. Standard errors are clustered at the state level. State dummies are included. Single, double, and triple asterisks (*, **, ***) denote significance at the 10%, 5%, and 1% levels, respectively.

Table 7. Summary of the Impact of NMP Compliance

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Associated Variables	**Coeff.**	**Std. Err.**	**Coeff.**	**Std. Err.**	**Coeff.**	**Std. Err.**
Stage I (participation)							
NMP on CAFO in 2000	CAFO × NMP	1.309**	0.622	1.588***	0.443	−0.622***	0.235
NMP on CAFO in 2010	(CAFO × NMP+CAFO × 2010 × NMP)	0.934***	0.258	0.643**	0.260	0.345	0.252
Difference	CAFO × 2010 × NMP	−0.375	0.579	−0.945*	0.553	0.967***	0.335
Stage II (level)							
NMP on CAFO in 2000	CAFO × NMP	−0.706	0.786	−0.185	0.337	−0.228	0.319
NMP on CAFO in 2010	(CAFO × NMP+CAFO × 2010 × NMP)	−0.336	0.472	0.11	0.326	−0.279*	0.151
Difference	CAFO × 2010 × NMP	0.370	0.925	0.295	0.478	−0.051	0.387
Average marginal impact on the participation rate		0.157***	0.021	0.245***	0.045	0.029	0.064

Notes: Average marginal impact on the participation rate indicates the averaged percentage increase in the participation rate of management practices under the counterfactual scenario where noncompliant CAFOs adopt NMP management standards. Robust standard errors are reported. Standard errors for average marginal impacts are computed using the Delta method. Single, double, and triple asterisks (*, **, ***) denote significance at the 10%, 5%, and 1% levels, respectively.

Robustness Check

We conduct five tests to examine the robustness of the results. First, we include farm size as an exogenous variable on the right sides of equations (1) and (3). The results are reported in Online Supplement Tables S9 and S10. The signs of the coefficients of the CAFO indicators and the interaction terms are essentially the same as those reported in Tables 5 and 6. Therefore, including the farm size variable does not change the implication that CAFOs in compliance with NMPs were more likely to build on-farm manure storage capacity and to apply manure on land.

Second, we estimate the double-hurdle model using a subsample of the farms with the number of cows between the 25th and 99th percentiles each year.[30] In 2000 and 2010, the 25th percentiles of farm sizes are 50 and 47 and the 99th percentiles are 2,150 and 3,752, respectively. The goal is to determine whether excluding small or extremely large farms in the sample affects the results. The results are shown in Online Supplement Tables S11 and S12. We find that estimated coefficients associated with the implementation of manure storage and land application are positive and significant for the CAFOs following NMP standards. This indicates that the main implication of this analysis does not change when excluding the small and extremely large farms.

Third, we estimate the model using the subsample without observations in New Mexico and Washington, which might be regulated under more stringent policies, as discussed previously. The results, reported in Online Supplement Tables S13 and S14, are similar to those of our main specification—no evidence of overall management practice adjustment, but strong evidence of higher participation rate for manure storage and land application. This again suggests that the main implication does not change by excluding farms in New Mexico and Washington.

Fourth, we analyze the subsample excluding farms with storage capacity of 0 or above the 95th percentile in order to analyze the subsample where the average storage capacities between 2000 and 2010 are more comparable. As we exclude farms with 0 storage capacity, the double-hurdle model is no longer applicable for analyzing storage capacity because the first stage of the model requires observations with 0 management practice values. Therefore, we estimate a log-linear model to analyze the impact of CWA on its level of implementation. Online Supplement Tables S15 and S16 present the results. We find no significance impact of CWA on the management practice implementation levels, which is consistent with our main finding.

Finally, we estimate the model without farm characteristics. The results are presented in Online Supplement Tables S17 and S18. Similarly, we find a positive effect on the implementation of manure storage and land application for CAFOs that comply with NMPs. These robustness tests support the conclusion that the CAFOs in compliance with NMPs are on average more likely to implement manure storage and land application but not for those failing to comply.

Conclusion

Analyzing dairy operations across the United States, we find that dairy CAFOs were on average more likely to adopt NMP management standards after the 2003 revision of the CWA. Compliant CAFOs are more likely than noncompliant CAFOs to implement manure storage and land application. There were, however, no significant overall change in storage capacity and land application for those CAFOs that had already implemented these practices. We also find no evidence of management practice adjustment by CAFOs that did not follow NMPs. This implies that the impact of the CWA on farm management is limited and only on the implementation of manure storage and land application for CAFOs in compliance with NMPs.

Our results are consistent with the policy enforcement issues frequently discussed in the literature. For example, Zande (2009) argues that enforcement of the CWA has been weak. Some

[30] We choose the 99th percentile because choosing lower percentiles will exclude most of the CAFOs in 2000. For example, the 95th percentile of farm size in 2000 is 746 cows. There are no CAFOs smaller than this threshold in the 2000 sample.

CAFOs did not apply for permits even though they were required to do so. Merkel (2006) suggests that EPA oversight is often lacking. The authorities are required to inspect the management practices of dairy CAFOs only once every 5 years (U.S. Environmental Protection Agency, 2004). In addition, the EPA did not have comprehensive data on the national statistics and operations of dairy CAFOs, which makes it difficult to enforce the policy. A reflexive policy design providing market-based incentives might improve regulation enforcement (Marble, 2013).

The results of this study appear to be conflicting but are actually compatible with the water quality improvement found in the literature (e.g., Lyon and Stein, 2009; Keiser and Shapiro, 2019) for the following reasons: First, this analysis focuses exclusively on dairy operations. Farmers of other livestock operations might react to the regulations differently. Second, farm management is not the only target of the CWA for reducing water pollution. The CWA also regulates pollutant discharges from municipal and industrial wastewater treatment plants (Copeland, 2016). Therefore, successful control of wastewater can lead to improvement in water quality, even though the regulation of CAFOs is effective only in a limited scope.

Future studies are encouraged to analyze the impact of farm management on water quality improvement. As discussed above, a large body of literature focuses on the effectiveness of the CWA. This study, on the other hand, analyzes farmers' responses to the policy. An analysis of how management practices affect the regulatory outcomes can fill the gap between the two streams of literature. In addition, we advocate the collection of more comprehensive data. Some detailed measures not available in the current ARMS data, such as manure application per acre of land and manure removal frequency, are also aspects of important farm management decisions.

[First submitted October 2019; accepted for publication October 2020.]

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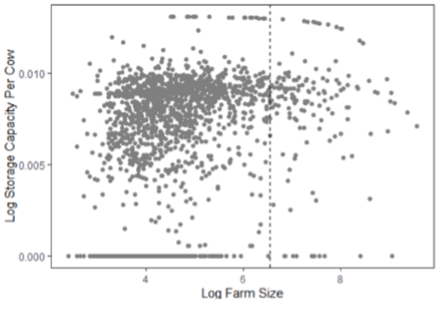
Journal of Agricultural and Resource Economics 46(3):S1–S19 ISSN 1068-5502

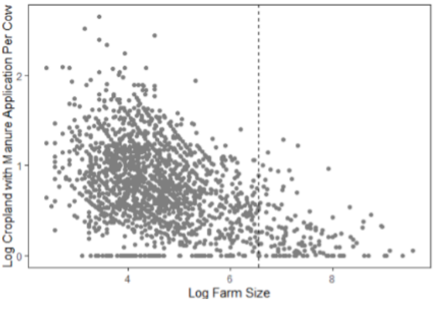
doi: 10.22004/ag.econ.307457

Online Supplement: The Impact of the Clean Water Act on Farm Practices: The Case of U.S. Dairy Concentrated Animal Feeding Operations

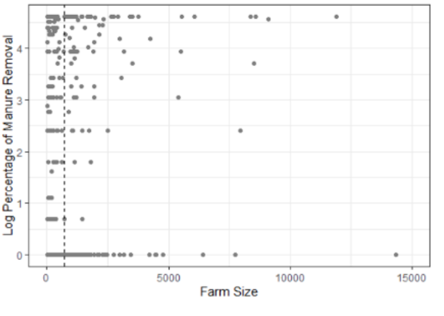
Charng-Jiun Yu, Xiaodong Du, and Daniel Phaneuf



(a) Storage Capacity per Cow



(b) Land with Manure Application per Cow



(c) Percentage of Manure

Figure S1. Log-Transformed Storage Capacity per Cow, Land with Manure Application per Cow, and Storage Capacity by Farm Herd Size for CAFOs in 2010

Notes: We use log transformation of both the management practice and farm size in panels a and b, and of management practice in panel c. To preserve zero values, we use $\log(x+1)$ to transform the data, where x is the management practice or farm size. Dashed lines indicate the threshold of large CAFOs. Note that the threshold is $\log(700)$ for panels a and b. Similar to Figure 2, we do not see distinctive changes in management practices around the CAFO threshold.

Table S1. Animal Units and CAFO Thresholds for Major Animal Types

Animal Type	CAFO Definitions			
	Large (≥1,000 AU)	Medium (300–999 AU)	Small (1–299 AU)	# of AU
Mature dairy cow	700	200–699	1–200	1.43
Feeder cattle	1,000	300–999	1–299	1
Swine (*geq*55 lbs)	2,500	750–2,499	1–749	0.4
Chicken	30,000	9,000–29,999	1–8,999	0.0333
Duck	5,000	1,500–4,999	1–1,499	0.2
Horse	500	150–499	1–149	2
Sheep	10,000	3,000–9,999	1–2,999	0.1

Notes: The AU values are based on the non-mixed category as defined in the federal regulations. The threshold and AU values for chickens and ducks are based on operations with liquid manure handling systems. Note that the thresholds for medium and small CAFOs are necessary but not sufficient for defining medium and small CAFOs. See Section 2 for a description of what constitutes a medium or small CAFO.

Table S2. Stringency Prohibitions of Major States

States	Stringency Prohibition	Selected Statutory Language	Reference
Arizona	Yes	"A. The director shall: . . . 2. Adopt, by rule, a permit program that is consistent with but no more stringent than the requirements of the clean water act for the point source discharge of any pollutant or combination of pollutants into navigable waters." (2001) "B. The director shall adopt rules to establish an AZPDES permit program consistent with the requirements of sections 402(b) and 402(p) of the clean water act. . . . The director shall not adopt any requirement that is more stringent than or conflicts with any requirement of the clean water act." (2001)	Ariz. Rev. Stat. Ann. § 49-203(A)(2) Ariz. Rev. Stat. Ann. § 49-255.01(B); Environmental Law Institute (2013).
California	No		
Colorado	Yes	". . . The provisions of any permit that are so required shall not be any more stringent than, and shall not contain any condition for monitoring or reporting in excess of, the minimum required by the federal act or regulations." (1981)	Colo. Rev. Stat. § 25-8-504(1); Environmental Law Institute (2013).
Florida	Yes/ Conditional	". . . The department may not adopt standards more stringent than federal regulations, except as provided in § 403.804..." (1982) "The department shall have a study conducted of the economic and environmental impact which sets forth the benefits and costs to the public of any proposed standard that would be stricter or more stringent than one which has been set by federal agencies pursuant to federal law or regulation." (1975)	Fla. Stat. Ann. § 403.061(7); Fla. Stat. Ann. § 403.804(2); Environmental Law Institute (2013).
Idaho	Yes	". . . It is the intent of the legislature that the state of Idaho fully meet the goals and requirements of the federal clean water act and that the rules promulgated under this chapter not impose requirements beyond those of the federal clean water act." (1995)	Idaho Code Ann. § 39-3601; Environmental Law Institute (2013).
New Mexico	No		
Texas	Yes/ Conditional	". . . (5) with respect to obtaining or administering the NPDES program in lieu of the government of the United States, not enter into any memorandum of agreement or other contractual relationship with or among state agencies or with the government of the United States which imposes any requirements upon the state other than or more stringent than those specifically set forth in Section 402(b) of the Federal Water Pollution Control Act, as amended." (1995)	Tex. Water Code Ann. § 26.017(5); Environmental Law Institute (2013).
Washington	No		
Wisconsin	Yes	" . . . all rules promulgated by the department under this chapter as they relate to point source discharges, effluent limitations, municipal monitoring requirements, standards of performance for new sources, toxic effluent standards or prohibitions and pretreatment standards shall comply with and not exceed the requirements of the federal water pollution control act, 33 USC 1251 to 1387, and regulations adopted under that act." (1985)	Wisc. Stat. Ann. § 283.11(2); Environmental Law Institute (2013).

Notes: Years of enactment of the statutory language are shown in parentheses in the "Selected Statutory Language" column (Environmental Law Institute, 2013). This table does not include all statutory languages regarding the stringency prohibition. For a more comprehensive list, see Environmental Law Institute (2013).

Table S3. Summary Statistics of Management Practices in 2000 and 2010 for All Farms

	Units	2000	2010
Storage capacity	1,000 gallons		
Mean		1,836.14	7,356.29
Std. dev.		8,643.81	52,990.48
Median		78.70	242.99
Land application	Acres		
Mean		127.02	171.90
Std. dev.		254.99	288.08
Median		80.00	100.00
Manure removal	%		
Mean		8.69	6.28
Std. dev.		26.24	21.81
Median		0.00	0.00
Storage capacity per cow	1,000 gallons/head		
Mean		9.07	12.30
Std. dev.		56.82	52.54
Median		0.97	2.78
Land application per cow	Acres/head		
Mean		1.25	1.41
Std. dev.		1.34	1.25
Median		0.95	1.11
Farm size	Head		
Mean		197.99	285.81
Std. dev.		375.85	837.89
Median		82.50	80.00
No. of obs.		865	1,893

Notes: These are the sample statistics without applying sampling weights. See Table 1 for the estimated population statistics after applying sampling weights.

Table S4. Summary Statistics of Management Practices in 2000 and 2010 for CAFOs

	Units	2000	2010
Storage capacity	1,000 gallons		
Mean		8,675.33	63,374.04
Std. dev.		15,151.77	168,372.39
Median		3,379.26	8,293.83
Land application	Acres		
Mean		393.65	562.34
Std. dev.		902.08	798.88
Median		130.00	300.00
Manure removal	%		
Mean		45.50	34.02
Std. dev.		45.57	41.41
Median		45.00	7.50
Storage capacity per cow	1,000 gallons/head		
Mean		6.93	30.88
Std. dev.		10.30	82.72
Median		3.65	6.37
Land application per cow	Acres/head		
Mean		0.35	0.35
Std. Dev.		1.08	0.48
Median		0.13	0.20
Farm size	Head		
Mean		1,387.44	2,211.57
Std. Dev.		779.88	2,162.62
Median		1,111.75	1,430.00
No. of obs.		52	150

Notes: These are the sample statistics without applying sampling weights. See Table 3 for the estimated population statistics after applying sampling weights.

Table S5. *t*-Statistics of the Welch's *t*-Test for the Equality of Mean Management Practices between 2000 and 2010

	t-Statistics
Storage capacity	−2.34**
Land application	−1.37
Manure removal	1.68*
Storage capacity per cow	−2.08**
Land application per cow	0.02
No. of obs.	202

Notes: * and ** denote significance at the 10% and 5% levels, respectively.

Table S6. Storage Capacity, Land Application, and Manure Removal for CAFOs in Sampled State

	Storage Capacity per Cow (1,000 gallons/ head)		Land Application per Cow (acres/head)		Manure Removal (%)	
	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
Arizona	5.18	4.84	0.03	0.08	86.96	29.34
California	42.00	104.52	0.20	0.23	37.43	42.73
Colorado	71.61	99.85	0.14	0.14	46.00	36.65
Florida	15.63	34.03	0.34	0.43	10.63	27.20
Georgia	161.62	209.36	0.16	0.02	2.50	3.56
Idaho	25.70	82.90	0.27	0.34	33.60	40.30
Illinois	N/A	N/A	N/A	N/A	N/A	N/A
Indiana	11.34	2.73	0.22	0.31	77.50	31.82
Iowa	2.91	3.16	0.36	0.51	50.00	70.71
Kansas	5.49	3.61	0.41	0.31	35.00	44.44
Kentucky	N/A	N/A	N/A	N/A	N/A	N/A
Maine	N/A	N/A	N/A	N/A	N/A	N/A
Michigan	10.31	5.26	0.41	0.21	62.00	10.58
Minnesota	6.02	N/A	0.28	N/A	0.00	N/A
Missouri	N/A	N/A	N/A	N/A	N/A	N/A
New Mexico	1.79	2.20	0.15	0.17	47.83	47.51
New York	8.96	5.17	1.20	0.38	0.83	2.04
Ohio	4.92	0.80	0.03	0.04	55.00	63.64
Oregon	18.58	14.01	0.45	0.30	16.00	16.36
Pennsylvania	5.02	N/A	0.67	N/A	0.00	N/A
Tennessee	N/A	N/A	N/A	N/A	N/A	N/A
Texas	37.46	93.44	0.88	2.16	25.83	39.36
Vermont	9.93	N/A	0.98	N/A	0.00	N/A
Virginia	N/A	N/A	N/A	N/A	N/A	N/A
Washington	6.41	5.32	0.40	0.40	22.55	38.85
Wisconsin	7.76	5.26	1.43	0.76	0.00	0.00

Notes: N/A is reported when there is no CAFO for the state in our sample. In addition, if there is only one CAFO in the state, standard deviation cannot be computed, so that N/A is reported.

Table S7. Summary Statistics of Management Practices in 2000 and 2010

		2000		2010	
	Units	**All Farms**	**CAFO**	**All Farms**	**CAFO**
Total land	Acres/head				
Mean		4.84	0.69	4.72	0.72
Std. dev.		5.52	1.26	4.82	0.92
Median		3.86	0.36	3.59	0.38
Total debts	$1,000/head				
Mean		1.65	1.5	2.03	1.98
Std dev.		2.23	1.04	2.69	1.71
Median		1.21	1.55	1.29	1.66
Total asset value	$1,000/head				
Mean		7.31	1.93	11.26	3.04
Std. dev.		8.89	2.22	11.53	2.27
Median		5.13	1.53	8.58	2.74
Labor hours	Hours/week/head				
Mean		1.4	0.37	1.56	0.61
Std. dev.		0.96	0.39	1.24	0.75
Median		1.23	0.21	1.24	0.53
No. of obs.		865	52	1893	150

Notes: These are the sample statistics without applying sampling weights. The total farm assets and total debts are converted to the real dollar values using the Consumer Price Index with 2000 as the base year.

Table S8. Regression Results of the Effect of CWA on NMP Compliance

	Dependent Variable: NMP Compliance Indicator	
	Coeff.	**Std. Err.**
Year 2010	0.163***	0.034
Total land	−0.005**	0.002
Total debt	0.011**	0.004
Total asset value	−0.001	0.001
Labor hours	−0.061***	0.012
Intercept	0.644***	0.162

Notes: The dependent variable is the dummy variable indicating the NMP compliance. State dummies are included. Results of state dummies are not reported because of space limitation and are available upon request. **, and *** denote significance at the 5%, and 1% levels, respectively.

Table S9. Regression Results of the Overall Effect of the CWA on Management Practices for CAFOs with "Farm Size"

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		0.070	0.273	−0.039	0.302	0.342	0.348
CAFO × 2010		0.012	0.422	−0.129	0.247	0.190	0.352
Farm size	100 head	0.007	0.013	−0.002	-0.005	0.001	0.005
Total land	Acres/head	−0.018*	0.010	0.107***	0.031	−0.189***	0.041
Total debt	$1,000/head	0.059***	0.011	0.0006	0.022	0.004	0.020
Total asset value	$1,000/head	−0.011***	0.003	−0.0001**	0.007	0.002	0.007
Labor hours	Hours/week/head	−0.119***	0.041	−0.083*	0.046	−0.006	0.034
Year 2010		0.414***	0.086	0.322***	0.107	−0.281**	0.135
Intercept		1.723***	0.218	1.032***	0.188	−0.237	0.301
Stage II (level)							
CAFO		−0.242	0.440	−0.269	0.202	−0.041	0.160
CAFO × 2010		0.607*	0.340	−0.188	0.254	0.085	0.239
Farm size	100 head	0.001	0.009	−0.008**	0.004	0.005	0.005
Total land	Acres/head	−0.024*	0.014	0.028***	0.006	−0.159**	0.064
Total debt	$1,000/head	0.040**	0.018	−0.004	0.006	0.029	0.026
Total asset value	$1,000/head	0.001	0.005	0.007***	0.002	0.031	0.012
Labor hours	Hours/week/head	−0.057**	0.027	0.032**	0.015	0.101	0.067
Year 2010		0.085	0.118	0.065	0.047	−0.372*	0.193
Intercept		8.416***	0.303	0.081	0.244	3.846***	0.256
No. of obs.		2,758		2,758		2,758	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S10. Regression Results of the Effect of NMP Compliance on Management Practices for CAFOs with "Farm Size"

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		−0.461	0.307	−0.684*	0.404	0.682	0.463
CAFO × 2010		−0.176	0.529	0.006	0.384	−0.430	0.513
CAFO × NMP		1.278**	0.610	1.587***	0.442	−0.621***	0.238
CAFO × 2010 × NMP		−0.313	0.559	−0.943*	0.549	0.967***	0.342
Farm size	100 head	0.008	0.013	−0.0009	0.005	0.0002	0.005
Total land	Acres/head	−0.017*	0.010	0.108***	0.032	−0.189***	0.041
Total debt	$1,000/head	0.058***	0.011	−0.005	0.021	0.003	0.020
Total asset value	$1,000/head	−0.011***	0.003	0.0003	0.007	0.002	0.007
Labor hours	Hours/week/head	−0.118***	0.041	−0.081**	0.045	−0.008	0.034
Year 2010		0.416***	0.086	0.324	0.106	−0.283**	0.135
Intercept		1.714***	0.221	1.026	0.191	−0.239	0.299
Stage II (level)							
CAFO		0.178	0.511	−0.123	0.196	0.049	0.232
CAFO × 2010		0.484	0.761	−0.390*	0.236	0.218	0.377
CAFO × NMP		−0.705	0.775	−0.2	0.339	−0.215	0.318
CAFO × 2010 × NMP		0.369	0.922	0.266	0.466	−0.057	0.385
Farm size	100 head	0.0004	0.0083	−0.008**	0.003	0.004	0.005
Total land	Acres/head	−0.024*	0.014	0.028***	0.006	−0.159	0.064
Total debt	$1,000/head	0.041**	0.018	−0.004	0.006	−0.032	0.026
Total asset value	$1,000/head	0.001	0.005	0.007***	0.002	0.031	0.012
Labor hours	Hours/week/head	−0.058**	0.027	0.032**	0.015	0.100	0.068
Year 2010		0.084	0.117	0.064	0.047	−0.376*	0.194
Intercept		8.421***	0.301	0.081	0.244	3.860***	0.257
No. of obs.		2,758		2,758		2,758	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S11. Regression Results of the Overall Effect of the CWA on Management Practices for CAFOs with Farm Size between 25th and 99th Percentile

		Storage Capacity (gallons/head)		Land with Manure Application (acres/head)		Percentage of Manure Removal (%)	
		1		2		3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		0.218	0.306	−0.085	0.285	0.366	0.344
CAFO × 2010		−0.109	0.413	−0.047	0.232	0.189	0.344
Total land	Acres/head	−0.025**	0.013	0.098**	0.042	−0.185***	0.054
Total debt	$1,000/head	0.056***	0.019	0.002	0.026	0.022	0.020
Total asset value	$1,000/head	−0.007	0.005	−0.002	0.011	0.005	0.010
Labor hours	Hours/week/head	−0.059	0.070	−0.106	0.077	0.029	0.052
Year 2010		0.440***	0.138	0.325**	0.133	−0.317*	0.163
Intercept		1.667***	0.097	0.996***	0.242	−0.404	0.439
Stage II (level)							
CAFO		−0.255	0.389	−0.287	0.205	−0.030	0.179
CAFO × 2010		0.590	0.376	−0.231	0.238	0.243	0.226
Total land	Acres/head	−0.025**	0.012	0.036***	0.011	−0.091	0.067
Total debt	$1,000/head	0.041*	0.022	−0.007	0.006	0.013	0.031
Total asset value	$1,000/head	0.004	0.005	0.008**	0.003	0.016	0.013
Labor hours	Hours/week/head	0.015	0.055	0.053*	0.027	0.153**	0.066
Year 2010		0.076	0.134	0.062	0.055	−0.531***	0.199
Intercept		8.432***	0.195	−0.026	0.223	3.647***	0.228
No. of obs.		2,007		2,007		2,007	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. “Year 2010” in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S12. Regression Results of the Effect of NMP Compliance on Management Practices for CAFOs with Farm Size between 25th and 99th Percentile

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		−0.434	0.300	−0.694*	0.397	0.659	0.467
CAFO × 2010		−0.352	0.624	−0.092	0.446	−0.476	0.529
CAFO × NMP		5.474***	0.357	1.540***	0.471	−0.537**	0.225
CAFO × 2010 × NMP		−4.236***	0.571	−0.705	0.630	0.984**	0.398
Total land	Acres/head	−0.024*	-0.024	0.095**	0.043	−0.185***	0.055
Total debt	$1,000/head	0.054***	0.054	−0.011	0.026	0.019	0.020
Total asset value	$1,000/head	−0.008	-0.008	−0.0004	0.012	0.006	0.010
Labor hours	Hours/week/head	−0.055	-0.055	−0.107	0.076	0.032	0.053
Year 2010		0.447***	0.138	0.335**	0.132	−0.311*	0.164
Intercept		1.675***	0.096	0.986***	0.243	−0.412	0.436
Stage II (level)							
CAFO		0.142	0.522	−0.066	0.165	0.070	0.261
CAFO × 2010		0.042	0.854	−0.426**	0.203	0.514	0.367
CAFO × NMP		−0.682	0.801	−0.300	0.281	−0.268	0.338
CAFO × 2010 × NMP		0.863	0.939	0.286	0.387	−0.249	0.391
Total land	Acres/head	−0.025**	0.012	0.036***	0.011	−0.092	0.063
Total debt	$1,000/head	0.041*	0.023	−0.005	0.006	0.028	0.040
Total asset value	$1,000/head	0.005	0.005	0.010***	0.003	0.018	0.013
Labor hours	Hours/week/head	0.013	0.055	0.056**	0.028	0.149**	0.066
Year 2010		0.074	0.133	0.058	0.055	−0.531***	0.201
Intercept		8.433***	0.194	−0.083	0.202	3.651***	0.234
No. of obs.		2,007		2,007		2,007	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S13. Regression Results of the Overall Effect of the CWA on Management Practices for CAFOs Excluding Farms in New Mexico and Washington State

	Unit	Storage Capacity (gallons/head)		Land with Manure Application (acres/head)		Percentage of Manure Removal (%)	
		1		2		3	
		Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		0.482	0.398	−0.061	0.308	0.482	0.398
CAFO × 2010		−0.224	0.505	−0.108	0.298	−0.224	0.505
Total land	Acres/head	−0.018*	0.010	0.115***	0.034	−0.018*	0.010
Total debt	$1,000/head	0.058***	0.011	−0.006	0.023	0.058***	0.011
Total asset value	$1,000/head	−0.012***	0.003	0.006	0.006	−0.012***	0.003
Labor hours	Hours/week/head	−0.121***	0.041	−0.094*	0.048	−0.121***	0.041
Year 2010		0.421	0.086	0.289***	0.109	0.421***	0.086
Intercept		1.738	0.219	1.009***	0.197	1.738***	0.219
Stage II (level)							
CAFO		0.166	0.355	−0.447**	0.216	0.166	0.355
CAFO × 2010		0.284	0.312	−0.106	0.213	0.284	0.312
Total land	Acres/head	−0.023	0.015	0.029***	0.006	−0.023	0.015
Total debt	$1,000/head	0.041**	0.019	−0.006	0.006	0.041**	0.019
Total asset value	$1,000/head	0.001	0.005	0.006***	0.002	0.001	0.005
Labor hours	Hours/week/head	−0.067**	0.028	0.030**	0.014	−0.067**	0.028
Year 2010		0.031	0.103	0.060	0.049	0.031	0.103
Intercept		8.471***	0.306	0.074	0.246	8.471***	0.306
No. of obs.		2,656		2,656		2,656	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S14. Regression Results of the Effect of NMP Compliance on Management Practices for CAFOs Excluding Farms in New Mexico and Washington State

		Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		−0.284	0.326	−0.955***	0.323	0.942	0.685
CAFO × 2010		−0.178	0.610	0.267	0.304	−0.799	0.68
CAFO × NMP		4.986***	0.386	1.992***	0.475	−0.604	0.503
CAFO × 2010 × NMP		−3.960***	0.475	−1.321**	0.602	1.051*	0.554
Total land	Acres/head	−0.017*	0.010	0.117***	0.035	−0.203***	0.044
Total debt	$1,000/head	0.057***	0.011	−0.012	0.022	0.013	0.019
Total asset value	$1,000/head	−0.012***	0.003	0.006	0.006	−0.005	0.007
Labor hours	Hours/week/head	−0.121***	0.041	−0.092**	0.046	0.008	0.033
Year 2010		0.424***	0.087	0.292***	0.108	−0.225	0.144
Intercept		1.729***	0.221	1.000***	0.200	−0.239	0.301
Stage II (level)							
CAFO		0.661	0.453	0.055	0.255	−0.087	0.261
CAFO × 2010		0.144	0.754	−0.541**	0.254	0.436	0.375
CAFO × NMP		−0.774	0.976	−0.627**	0.311	0.108	0.325
CAFO × 2010 × NMP		0.353	1.092	0.554	0.414	−0.359	0.397
Total land	Acres/head	−0.023	0.015	0.029***	0.006	−0.174**	0.071
Total debt	$1,000/head	0.042**	0.019	−0.006	0.006	0.028	0.026
Total asset value	$1,000/head	0.001	0.005	0.007***	0.002	0.026**	0.013
Labor hours	Hours/week/head	−0.068**	0.028	0.030**	0.014	0.011	0.067
Year 2010		0.031	0.102	0.06	0.049	−0.21	0.19
Intercept		8.476***	0.304	0.074	0.246	3.760***	0.268
No. of obs.		2,656		2,656		2,656	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S15. Regression Results of the Overall Effect of the CWA on Management Practices Excluding Farms with Storage Capacity of Zero or above 95th Percentile

		Log Storage Capacity (gallons/head)		Log Land with Manure Application (acres/head)		Log Percentage of Manure Removal (%)	
		1		2		3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		−1.741**	0.652	−0.564*	0.255	0.048	0.459
CAFO × 2010		1.232*	0.628	−0.148	0.291	−0.064	0.569
Total land	Acres/head	−0.018	0.015	0.039***	0.007	−0.179*	0.090
Total debt	$1,000/head	0.036*	0.020	−0.010*	0.005	0.025	0.036
Total asset value	$1,000/head	0.001	0.005	0.006***	0.002	0.032*	0.018
Labor hours	Hours/week/head	−0.043	0.030	0.054**	0.024	0.201***	0.070
Year 2010		0.114	0.117	0.152**	0.068	0.449**	0.212
Intercept		8.081***	0.164	−0.600**	0.250	3.629***	0.311
No. of obs.		1,958		1,958		1,958	

Notes: The dependent variables are listed in the top row. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S16. Regression Results of the Effect of the NMP Compliance on Management Practices Excluding Farms with Storage Capacity of Zero or above 95th Percentile

		Log Storage Capacity (gallons/head) 1		Log Land with Manure Application (acres/head) 2		Log Percentage of Manure Removal (%) 3	
	Unit	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO		−2.114*	1.126	−0.476	0.451	−2.114*	1.126
CAFO × 2010		0.617	1.120	−0.642	0.541	0.617	1.120
CAFO × NMP		0.525	1.185	−0.117	0.434	0.525	1.185
CAFO × 2010 × NMP		0.581	1.100	0.558	0.675	0.581	1.100
Total land	Acres/head	−0.018	0.015	0.039***	0.007	−0.018	0.015
Total debt	$1,000/head	0.035*	0.020	−0.010*	0.005	0.035*	0.020
Total asset value	$1,000/head	0.001	0.005	0.006***	0.002	0.001	0.005
Labor hours	Hours/week/head	−0.042	0.030	0.054*	0.024	−0.042	0.030
Year 2010		0.116	0.117	0.558	0.068	0.116	0.117
Intercept		8.084***	0.162	−0.599**	0.251	8.084***	0.162
No. of obs.		2,656		2,656		2,656	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S17. Regression Results of the Overall Effect of the CWA on Management Practices for CAFOs without Farm Characteristics

	Storage Capacity (gallons/head) 1		Land with Manure Application (acres/head) 2		Percentage of Manure Removal (%) 3	
	Coeff.	**Std. Err.**	**Coeff.**	**Std. Err.**	**Coeff.**	**Std. Err.**
CAFO	0.316	0.312	−0.192	0.268	0.685**	0.297
CAFO × 2010	0.104	0.405	−0.108	0.250	0.136	0.335
Year 2010	0.375***	0.076	0.270**	0.109	−0.219*	0.114
Intercept	1.301***	0.206	1.559***	0.156	−1.246***	0.287
Stage II (level)						
CAFO	−0.129	0.396	−0.441*	0.232	0.123	0.181
CAFO × 2010	0.606	0.368	−0.279	0.222	0.041	0.254
Year 2010	0.105	0.113	0.085	0.053	−0.253	0.203
Intercept	8.184***	0.302	0.397*	0.238	3.670***	0.219
Likelihood ratio test statistic against the full model (with farm characteristics)	94***		222***		140***	
Likelihood ratio test statistic against the intercept-only model	673***		1,549***		557***	
No. of obs.	2,758		2,758		2,758	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. "Year 2010" in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. The highly significant likelihood ratio test statistics against the full model suggests that the farm characteristics have strong explanatory power. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table S18. Regression Results of the Effect of NMP Compliance on Management Practices for CAFOs without Farm Characteristics

	Storage Capacity (gallons/head)		Land with Manure Application (acres/head)		Percentage of Manure Removal (%)	
	1		2		3	
	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
CAFO	−0.226	0.331	−0.847**	0.373	1.021**	0.433
CAFO × 2010	−0.080	0.545	0.074	0.346	−0.523	0.512
CAFO × NMP	1.351**	0.663	1.604***	0.428	−0.619**	0.278
CAFO × 2010 × NMP	−0.348	0.613	−1.005*	0.534	1.011***	0.372
Year 2010	0.377***	0.077	0.270**	0.109	−0.221*	0.115
Intercept	0.130***	0.209	1.555***	0.158	−1.249***	0.285
Stage II (level)						
CAFO	0.264	0.487	−0.300	0.217	0.215	0.250
CAFO × 2010	0.452	0.758	−0.487*	0.269	0.153	0.375
CAFO × NMP	−0.666	0.784	−0.193	0.350	−0.225	0.284
CAFO × 2010 × NMP	0.387	0.918	0.271	0.489	−0.029	0.359
Year 2010	0.104	0.113	0.085	0.053	−0.257	0.204
Intercept	8.186***	0.300	0.396*	0.239	3.688***	0.219
Likelihood ratio test statistic against the full model (with farm characteristics)	92***		224***		139***	
Likelihood ratio test statistic against the intercept-only model	789***		1,569***		562***	
No. of obs.	2,758		2,758		2,758	

Notes: The dependent variables are listed in the top row. The first column lists the corresponding independent variables. “Year 2010” in the first column refers to the dummy variable of 2010. Standard errors are clustered at the state level. State dummies are included. The highly significant likelihood ratio test statistics against the full model suggests that the farm characteristics have strong explanatory power. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

NPDES Permit Regulatory Details

This section describes the regulatory details of the NPDES permit for large dairy CAFOs. The NPDES permit specifies four sets of requirements: (i) effluent limitations, (ii) special conditions, (iii) standard conditions, and (iv) monitoring, record keeping, and reporting, which are applicable to CAFO farmers who can potentially discharge pollutants to U.S. surface water and groundwater (U.S. Environmental Protection Agency, 2003).

Effluent limitations describe the common requirements CAFO farmers need to follow regarding their management practices. Three categories of effluent limitations, (i) technology-based effluent limitations, (ii) water-based effluent limitations, and (iii) best management practices, can be specified in the permit. Among the six types of technology-based limitations, the Best Practicable Control Technology Currently Available (BPT) has several important requirements regulating the storage facility and land application by CAFOs.[1] As the regulation requires the production area to be "designed, constructed, operated and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 25-year, 24-hour rainfall event" (40 CFR § 412.31), CAFO owners or operators must submit a technical analysis to support their ability to meet this requirement. The technical analysis should include the predicted median annual overflow volume, predicted annual average discharge of pollutants, and pollutant data with nitrogen and phosphorus content, as well as other information relevant to farm operation. For the requirement on land applications, CAFO farmers must develop and implement the best management practices and keep appropriate records.

Special conditions specify individual requirements based on the unique condition of each CAFO. There are at least three special conditions for large dairy CAFOs. First, CAFO farmers must develop and implement a NMP. The NMP contains the management practices necessary to meet the requirements of effluent limitations as well as some additional requirements. For example, the NMP must ensure "adequate storage of manure, litter, and process wastewater, including procedures to ensure proper operation and maintenance of the storage facilities," "prevent direct contact of confined animals with waters of the United States," and "establish protocols to land apply manure, litter or process wastewater" (40 CFR § 122.42). Second, CAFO farmers must comply with certain rules when transferring the manure, litter, or process wastewater to other people. For example, CAFO farmers must provide the nutrient information to the recipient and keep records of the transferring activities. Third, CAFOs farmers must maintain permit coverage until the operation is closed. Some additional special conditions, such as the restriction on applying manure to frozen ground and requirement on specific manure application methods, might also be included in the permit.

Standard conditions contain rules about the operation and maintenance of the CAFOs, which are applicable to all permits. For example, (i) CAFO farmers must reapply for a new permit after expiration if they want to continue their operation; (ii) the permit holders must "properly operate and maintain all facilities and systems of treatment and controls (and related appurtenances) which are installed or used by the permittee to achieve compliance with the conditions of this permit" (40 CFR § 122.41); and (iii) permit holders must allow permit authorities to perform proper inspection.

Monitoring, record keeping, and reporting requires that CAFO farmers monitor their operations, record operational information, and report to the permit authority accordingly. Some examples of requirements include analyzing the nitrogen and *E. coli* content of discharges (monitoring), maintaining records to support adequate storages (record-keeping), and submitting annual reports including the number of cows, estimated total amount of manure, the total number of acres of land application, and so forth (reporting).

CAFOs that have no potential to discharge do not need a permit. According to the U.S. Environmental Protection Agency (2003), the "no potential to discharge" is qualified if (i) the owner

[1] Other five types of technology-based limitations are Best Conventional Pollutant Control Technology (BCT), Best Available Technology Economically Achievable (BAT), New Source Performance Standards (NSPS), Pretreatment Standards for New Sources (PSNS), and Pretreatment Standards for Existing Sources (PSES).

or operator demonstrates that the manure, litter, and process wastewater from the operation are not possible to contact the surface water and (ii) no discharge has been made in the operation over the past 5 years. An example of such CAFOs could be one that does not land apply manure on the production area, has appropriate storage to hold manure and wastewater even under severe rainfall events, and is located very far away from any surface water.

[Received October 2019; final revision received October 2020.]

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