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LEAN AND GREEN? AN EMPIRICAL EXAMINATION OF
THE RELATIONSHIP BETWEEN LEAN PRODUCTION
AND ENVIRONMENTAL PERFORMANCE*

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Lean production may have a significant public good spillover—improved environmental performance. However, empirical evidence of the link between lean production practices and environmental performance has not resolved the nature of the relationship. To explore this issue, we conduct an empirical analysis of the environmental performance of 17,499 U.S. manufacturing establishments during the time period 1991-1996. We find that those establishments that adopt the quality management standard ISO 9000 are more likely to adopt the environmental management standard ISO 14000. We also find strong evidence that lean production, as measured by ISO 9000 adoption and low chemical inventories, is complementary to waste reduction and pollution reduction.
(LEAN PRODUCTION; ENVIRONMENTAL PERFORMANCE: ISO 9000; ISO 14000)

A number of authors have proposed that the adoption of lean production can directly improve the public good by improving the environmental performance of the adopting firms (Florida 1996; Hart 1997). According to this logic, the “good housekeeping” practices associated with lean production have the subsidiary benefit of reducing spills and other forms of waste. Hence, scholars propose that the adoption of lean production practices will improve the environmental performance of manufacturing establishments; in other words, lean is green.

Empirical evidence of the link between lean production practices and environmental performance is sparse. Much of the work remains anecdotal, relying on individual success stories to support a relationship between lean production and environmental performance (Graedel and Allenby 1995). A few studies use questionnaires to demonstrate a possible association between leanness and greenness (Maxwell, Rothenberg, and Schenck 1993; Florida 1996; Rothenberg 1999). Unfortunately, they cannot rule out the possibility that both lean production and environmental improvement may be caused by other underlying firm attributes. For example, lean production may be related to pollution reduction only because both are the manifestation of the firm’s innovative nature.

In this paper, we extend the debate both theoretically and empirically. The adoption of lean practices may lead inadvertently to pollution reduction, may reduce barriers to implementing pollution reducing measures, or may simply provide information about the value of reducing pollution. We propose that lean may beget green because they are complements. Adopting

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lean production practices reduces the marginal cost of environmental management and leads to improved environmental performance. Thus we hypothesize that lean production will increase the likelihood that establishments will adopt advanced environmental management systems. Furthermore, we hypothesize that these gains will be achieved by source reduction, not end-of-pipe treatment. Finally, we hypothesize that facilities that adopt lean production systems will reduce emissions.

Empirically, we combine large-scale databases from several sources and cross-link the records, allowing far more detailed quantitative analysis of interactions between operational variables and environmental impact. We test our hypotheses through an empirical analysis of the environmental performance of 17,499 U.S. manufacturing establishments during the time period 1991-1996. We find strong evidence that establishments that minimize inventory and adopt quality standards are more likely to have lower emissions of toxic chemicals, and these facilities reduce emissions through pollution prevention rather than end-of-pipe treatment of waste. Finally, we find evidence that establishments that adopt the quality standard ISO 9000 are also more likely to adopt the environmental management standard ISO 14000.

Theory and Hypotheses

The concept of lean production arose from the study of Japanese manufacturing techniques, particularly in the automobile industry (Womack, Jones, and Roos 1990). Lean production relates to a number of practices touching on almost every aspect of a firm's operations. At its core are practices that relate to technical and human capabilities and to work place management (MacDuffie 1995). A chief issue is the management of inventory and rework "buffers," and the reduction of these buffers gives rise to the "lean production" name (Womack, Jones, and Roos 1990).

Proponents of a "lean is green" relationship provide several arguments (Florida 1996; Hart 1997). For one, the adoption of lean practices may lead inadvertently to pollution reduction. Some proponents observe that "zero waste" is the mantra of lean production and suggest that pollution reduction will inevitably follow from lean production. Critics point out, however, that reducing one factor of production may increase another. Efforts to increase the efficiency of throughputs may lead to a greater production of waste. Reducing inventory, for example, may lead to a greater production of waste. The small batch size production inherent in lean production entails more frequent changeovers, and these changeovers might require cleaning of production equipment and disposal of unused process material.

An alternative argument is that lean production may lead to less pollution by reducing the marginal cost of pollution reduction activities and thereby encouraging managers to invest in waste reduction. Research has demonstrated that lean production is enabled by, and helps to develop, process improvement capabilities (Womack, Jones, and Roos 1990). Lower inventory levels require workers to be more cognizant of change in the production process (MacDuffie 1995, 1997). Once workers have developed such awareness, teaching them additional related skills may require less investment.

Lean production may also reduce the cost of pollution reduction by reducing the cost of discovering opportunities for profitable pollution prevention. Theory suggests that a priori expectations and search costs can inhibit managers from uncovering existing opportunities for profit (Arrow 1974; Jensen 1982). If managers expect pollution-reduction to be costly, and it is difficult to do the measurement and analysis to test this expectation, managers may never investigate the real value of pollution reduction (Jensen 1982). As a result, opportunities for profitable pollution reduction may go unexploited. By providing new insight into the importance of indirect and distributed costs and benefits, lean production may provide managers with new expectations of the potential costs and benefits of pollution reduction activities.

Thus, engaging in lean production may reduce the marginal cost of pollution reduction

either by lowering the costs of implementing environmental improvement or by providing information about the value of pollution reduction. Consequently, we expect establishments that engage in lean manufacturing to adopt proactive environmental management practices. Environmental management systems (EMS) share many characteristics with lean production. Most EMSs emphasize formal monitoring and improvement of facility waste streams. Like lean production systems, they often include opportunities for collaborative problem solving and continuous improvement. Therefore we expect that firms that practice lean production will be more likely to adopt formal environmental management systems.

HYPOTHESIS 1. The more an establishment engages in lean production, the more likely it will adopt a formal environmental management system.

We expect spillovers from lean production to go beyond the adoption of environmental management systems. Scholars have proposed that lean production will lead to a different mix of pollution reduction activities (Hart 1997). In general, they argue that managers will increase the extent to which they reduce waste in the production process (often called source reduction or pollution prevention) and reduce the extent to which they treat waste onsite (U.S. Congress 1994; Hart 1995; Klassen and Whybark 1999). Reducing pollution in the process rather than treating it at the end-of-the-pipe has a similar logic to building quality into the product rather than inspecting it in at the end-of-the-line. Experience with lean production might help managers see the value in process improvement over end-of-line retrofit (King 1993). As a result, we propose that those firms that engage in lean manufacturing will substitute source reduction for end-of-pipe treatment. In other words, establishments that adopt lean production systems will achieve desired pollution levels through source reduction and therefore engage in less onsite treatment.

HYPOTHESIS 2. The more an establishment engages in lean production, a) the less it will generate waste at the source, and b) the less it will engage in end-of-pipe treatment.

Finally, we consider what is the net effect of these changes. If lean production facilitates source reduction activity, we expect that establishments that engage in lean production will have lower emissions. By reducing the marginal cost of pollution reduction, lean producing establishments will adopt environmental management practices that lead to reductions in waste generation at the source. While some of this pollution reduction may be offset by a relative decrease in onsite treatment, total emissions will be lower since the marginal cost of overall environmental improvement is lower.

HYPOTHESIS 3. The more an establishment engages in lean production, the lower will be its emissions.

Data and Measurement

Sample

Our sample is drawn from the population of U.S. manufacturing facilities during the period 1991-1996. We collected environmental performance data from the U.S. EPA's Toxic Release Inventory (TRI). Our data set was limited by the reporting requirements for TRI. Facilities must complete TRI reports if they manufacture more than 25,000 pounds or use more than 10,000 pounds of any listed chemical and employ 10 or more full-time people during the calendar year. Prior to 1991, firms did not need to report waste generated by the production process, so we cannot use TRI data prior to that year. Using all TRI reporting facilities, we created an unbalanced panel of 17,499 facilities constituting 88,531 facility-year observations for the years 1991 to 1996.

Dependent Variables

ENVIRONMENTAL PERFORMANCE. Previous research has measured the environmental performance of a firm as the degree to which that firm emits toxic pollution (Hart and Ahuja 1996).

To measure total firm emissions (*Total Emissions*), we used data on 246 toxic chemicals that have been consistently reported in the Toxic Release Inventory. We weigh each chemical by its toxicity using as our estimate of toxicity the threshold “reportable quantity” (RQ) for an accidental spill as required in the CERCLA statute (see King and Lenox 2000). We then sum all of the toxicity-weighted emissions for a facility in a given year to calculate the total pollution from the plant. To improve the distribution of the measure, we take the natural log of this sum.

$$Total\ Emissions_{it} = \ln \sum_c w_c e_{cit} \quad (1)$$

where $Total\ Emissions_{it}$ is aggregate emissions for facility i in year t , w_c is the toxicity weight for chemical c , and e_{cit} is the pounds of emissions of chemical c for facility i in year t .

Unfortunately, this measure of environmental performance fails to control for differences in production across industries and among different sized plants. We obviously expect that large facilities in more polluting industries would have higher emissions. Following King and Lenox (2000), we measure *relative* environmental performance at the facility level by estimating the production function relationship between facility size and aggregate toxic emissions for each four-digit standard industrial classification (sic) code within each year using an ordinary least-squares regression. The relative environmental performance of a facility (*Relative Emissions*) is given by the standardized residual, or deviation, between observed and predicted emissions given the facility's size and industry sector. Thus, if a facility emits more than predicted given its size and sic code, it will have a positive residual and a positive score for environmental impact. We estimate the production function and residual for each industry as follows:

$$\ln(E_{it}) = \alpha_{jt} + \beta_{1jt} \ln(s_{it}) + \beta_{2jt} \ln(s_{it})^2 + \epsilon_{jt} \quad (2)$$

$$Relative\ Emissions_{it} = \epsilon_{jt} / \sigma_{jt} \quad (3)$$

where E_{it} is the emissions for facility i in year t , s_{it} is facility size, σ_{jt} is the standard deviation of emissions for sector j , and α_{jt} , β_{1jt} , and β_{2jt} are the estimated coefficients for sector j in year t . The inclusion of the squared-term in Equation 2 allows for concave and convex production functions.

ENVIRONMENTAL MANAGEMENT. As discussed earlier, firms may manage their wastes in a number of ways. To differentiate source reduction activities (pollution prevention) from end-of-pipe treatment (pollution control), we generate two measures: *Waste Generation* and *Onsite Treatment*. Waste Generation measures the toxic chemicals produced by a facility before onsite treatment or transfer to offsite processing. Waste Generation is calculated in a similar manner as Relative Emissions. Waste Generation is the standardized residual from regressing total waste generation (rather than emissions) on facility size by four-digit sic code.

Onsite Treatment measures the degree to which waste is treated onsite as opposed to being released into the environment or transferred for third party processing. To generate this variable, we first calculate the percentage of the material processed onsite (burned, treated, or recycled) to the total waste generated. We then calculate the average and standard deviations for these amounts for each sic code in each year. From this we calculate a deviation for each facility.

In addition to Waste Generation and Onsite Treatment, we also measure whether a facility adopts the ISO 14001 environmental management standard. Recall that we hypothesize that lean production activities may lead to the adoption of environmental management systems. The ISO 14001 standard is the most prominent environmental management system in the United States. The standard was established in 1996 by the International Organization for

Standardization. ISO 14001 requires a facility to develop an environmental policy, set objectives, delineate organizational responsibilities, provide training and documentation, and monitor and correct deficiencies (ISO 2000). It is the environmental analogue to the ISO 9001 quality management standard. ISO 14001 *Adoption* is coded simply as a dummy where "1" indicates that a facility became ISO 14001 certified sometime during the period 1996-1999. Because ISO 14001 postdates our sample, our measure of ISO 14001 Adoption is not longitudinal. Certification data were gathered from the GlobeNet database of ISO 14001-certified firms (GlobeNet 2000).

Independent Variables

LEAN PRODUCTION. "Lean" production has been measured in a variety of ways. Researchers from the Massachusetts Institute of Technology's International Motor Vehicle Program (IMVP) use survey responses on (1) the use of buffers, (2) the use of work system teams, and (3) human resource management policies (MacDuffie 1991; Womack, Jones, and Roos 1990). While not explicitly adopting the label of "lean production," other empirical research combines technical measures of inventory with survey measures of management practices (Flynn, Schroeder, and Sakakibara 1995; Sakakibara, Flynn, Schroeder, and Morris 1997). Where survey measures are difficult to obtain, previous research has used certification of quality programs or reception of quality awards to measure adoption of management practices (Hendricks and Singhal 1997; Tai and Przasnyski 1999).

The extent to which lean production requires the adoption of both lower inventory and better work place management practices has been one area of debate. In a sample of 512 metal working companies, Snell and Dean (1992) found that lower inventory was actually negatively related to two of the IMVP-proposed attributes of lean work system management and human resource management (HRM) policies—selectivity and performance appraisal. In contrast, MacDuffie (1995) found that the combination of the three attributes led to better operational performance. Theoretical work on complementarities also supports the combinatory benefits of various lean production practices (Milgrom and Roberts 1995).

Because of the large size of our sample, we choose to use two measures that capture (1) the use of inventory buffers and (2) work system management that emphasizes (a) a pro-active and well-trained work force, (b) process measurement, and (c) continuous improvement. We remain open minded about whether each measure represents movement toward lean production or both must be present. Thus we include each measure separately in our analysis.

To capture the degree to which a firm uses inventory buffers, we use the TRI database to measure the maximum inventory of chemicals in a facility over the course of a year. Across all TRI "core" chemicals, we sum the maximum amount of chemical (in pounds) held onsite during the course of a year. We do not weight these chemicals by their toxicity because we think that toxicity is orthogonal to the issue of inventory buffers. (However, weighting by toxicity does not change our findings.) We then take the natural log of this measure to form our variable Maximum Inventory. This variable measures the maximum amount of raw materials, work in process, and finished goods for the 246 chemicals.

One of the key attributes of lean production is the use of management practices that support process and quality improvement (MacDuffie 1991). Daniel Roos, one of the originators of the concept of lean production, notes that ISO 9001 (a quality management standard created by the International Organization for Standardization) is often an "important step" toward lean production. It helps change the way "processes are organized" and makes sure that managers are "clear about their processes," but, he argues, its central ideas must be fully implemented for the facility to reach lean production (Sukumar 1997). ISO 9001 also changes management practices as required by lean production. According to the ISO, "The [ISO 9001] requirements include management, leadership, a pro-active and well-trained work force, customer feedback, measurement, documentation, internal audits, continuous improve-

ment, and third party validation" (ISO 2000). To be certified under the standard, facilities must demonstrate to third party certifiers that the facility has implemented programs congruent with process excellence and quality assurance. ISO 9001 Adoption is coded as a dummy where "1" indicates that the facility is ISO 9001 certified for that year. Certification data were gathered from the ISO 9001 Registered Company Directory of North America (McGrawHill 1998).

CONTROLS. We control for a number of facility attributes that likely influence the cost associated with polluting and therefore the degree to which a facility pollutes.

- *Facility size.* Facility size is measured as the natural log of the number of employees at the facility. Base-line data were gathered from the Dun and Bradstreet Data Set. Trend data are calculated using the production-ratios specified in the Toxic Release Inventory and are supplemented by industry data from the National Bureau of Economic Research when needed.
- *Abatement costs.* The costs associated with treating plant emissions, i.e., abatement costs, vary greatly across industries. Consequently, a given facility's emissions may be greatly influenced by the costs associated with abatement in that industry. The U.S. Bureau of the Census measures the costs of compliance to environmental regulations incurred by industry. The Pollution Abatement Capital Expenditures (PACE) and the Pollution Abatement Operating Costs (PAOC) datasets contain these costs at the four-digit SIC code. *Abatement Costs* is calculated as the log of total industry cost of abatement ($\text{PACE} + \text{PAOC}$).
- *Regulatory stringency.* Environmental regulation may vary across regions and impose greater (or lesser) penalties for pollution. In most cases, costs vary with state location. States have independent environmental protection agencies and state-specific regulations. Relative state regulatory stringency is constructed using a measure devised by Meyer (1995). Meyer found that state regulatory stringency with respect to manufacturing-based environmental regulation is inversely correlated with the log of the sum of toxic emissions divided by total employees in four main polluting industries—chemicals, petroleum, pulp and paper, and materials processing (Meyer 1995). This measure has the desirable property that it provides a clear ranking of states that is consistent and transparent over time. While arguments may abound concerning which states are stricter than others, the resulting ranking seems to be consistent with intuition, e.g., California and Massachusetts are ranked high while Louisiana is ranked low. We replicate the measure by using emissions data from the Toxic Release Inventory.
- *Permits.* The technological attributes of a facility's product and processes often influence the nature of government regulation applied to that site. The production of certain types of wastes and pollutants require government-approved permits (Tables 1 and 2). In particular, the U.S. EPA requires permits for water borne waste that does not go to waste treatment facilities (under the Clean Water Act) and for any hazardous waste that is produced or used (under the Resource Conservation and Recovery Act, RCRA). We created a measure of the regulatory stringency associated with a particular technology by counting the number of federal wastewater and hazardous waste permits possessed by a facility as reported in the U.S. EPA's Water Permit Compliance System (PCS) and the RCRA Information System (RCRIS); the greater the number of permits, the greater regulatory stringency the facility faces.

Methods

We use both a probit and two-staged least-squares (2SLS) specification to evaluate Hypothesis 1—the influence of lean production on the propensity to adopt environmental management systems. In both models, we use only one cross section of the data since our dependent variable (ISO 14001 Adoption) is not longitudinal. Facility data from 1995 are

TABLE 1
Descriptive Statistics

Variable	Description	Mean	Standard Deviation	Minimum	Maximum
<i>Environmental Performance & Management Variables</i>					
Total emissions	Natural log of total emissions of firm	2.80	2.64	0.00	15.81
Relative emissions	Relative emissions of facility based on sector and size	0.19	0.91	-7.08	12.73
Waste generation	Relative waste generated by facility based on sector and size	0.27	0.73	-5.21	4.68
Onsite treatment	Standardized ratio of onsite treatment to generated waste	0.01	1.00	-4.20	14.53
ISO 14001 Adoption	Binary variable indicating ISO 14001 adoption	0.02	0.11	0.00	1.00
<i>Lean Production Variables</i>					
ISO 9001 Adoption	Binary variable indicating ISO 9001 adoption	0.04	0.19	0.00	1.00
Maximum inventory	Maximum amount of material stored onsite over the course of a year	4.78	1.45	0.69	84.00
<i>Controls</i>					
Facility size	Natural log of facility employees	4.90	1.43	0.09	10.97
Regulatory stringency	The regulatory stringency of the facility's state	0.17	0.03	0.10	0.30
Abatement costs	Annual abatement costs for the facility's industry segment	159.45	398.13	0.00	4,887.90
Permits	The number of facility CWA and RCRA permits	0.36	0.52	0.00	3.00

Note: $n = 88,531$.

used since they immediately predate the onset of ISO 14001 certifications in 1996. In other words, we estimate whether a firm adopts ISO 14001 during the time period 1996-1999 given the characteristics of the establishment in 1995.

A probit model is used to correct for the fact that we have a discrete dependent variable (Greene 1993). The probit model provides an estimate of the likelihood that a facility adopts ISO 14001. The formal specification of the probit model is as follows:

TABLE 2
Correlations

	1	2	3	4	5	6	7	8	9	10	11
1. Total emissions	1.00										
2. Relative emissions	0.60*	1.00									
3. Waste generation	0.38*	0.62*	1.00								
4. Onsite treatment	0.05*	0.00	0.20*	1.00							
5. ISO 14001 Adoption	0.04*	0.01	0.01	0.02*	1.00						
6. ISO 9001 Adoption	0.01	0.00	0.00	0.01*	0.02*	1.00					
7. Maximum inventory	0.32*	0.14*	0.20*	0.12*	0.04*	0.04*	1.00				
8. Facility size	0.28*	-0.05*	-0.08*	0.07*	0.11*	0.07*	0.16*	1.00			
9. Regulatory stringency	-0.13*	-0.06*	-0.04*	-0.02*	0.00	0.01*	-0.09*	-0.05*	1.00		
10. Abatement costs	0.24*	0.00	-0.02*	0.01	0.01	0.03*	0.39*	0.03*	-0.06*	1.00	
11. Permits	0.20*	0.07*	0.07*	0.08*	0.04*	0.05*	0.27*	0.23*	-0.04*	0.20*	1.00

Note: $n = 88,531$. * $p < 0.001$.

$$\text{Prob}(\text{ISO 14001 Adoption} = 1) = \Phi(\beta'x) \quad (4)$$

where the vector x includes a constant and our independent variables, *ISO 9001 Adoption*, *Maximum Inventory*, *Relative Emissions*, *Facility Size*, *Firm ISO 14001 Adopters*, and *Industry ISO 14001 Adopters*. We include *Relative Emissions* because it is likely that dirtier facilities have more incentive to improve their environmental performance and hence to adopt environmental management practices. *Firm ISO 14001 Adopters* is the number of other facilities within the firm (to which the target establishment belongs) that adopt ISO 14001 between 1996 and 1999. This variable is included to control for firm level efforts to encourage adoption. Similarly, *Industry ISO 14001 Adopters* measures the number of other facilities that adopt ISO 14001 within a facility's industry. This variable is included to control for industry level factors that may encourage adoption. In one model, we also include dummy variables for each four digit SIC code. These variables should correct for any industry fixed effect that causes ISO 14001 adoption.

One weakness with the probit specification is that it fails to account for the endogeneity of *Relative Emissions*. If, as we speculate in later models, ISO 9001 adoption leads to lower relative emissions, we should explicitly include this interaction in our model. To control for the endogeneity of *Relative Emissions*, we use a 2SLS specification where we first estimate *Relative Emissions* then estimate ISO 14001 Adoption. In two-staged least squares, all the exogenous variables serve as instruments for the endogenous variables. We are able to identify each equation because we include in the first equation (our estimate of *Relative Emissions*) our measures of the regulatory environment—*Regulatory Stringency*, *Abatement Costs*, and *Permits*.

We estimate models using both specifications because we recognize that there is an inherent tradeoff between them. The probit specification addresses the fact that we have a discrete dependent variable but fails to account for the endogeneity of *Relative Emissions*. The two-stage model accounts for the potential endogeneity but treats the dependent variable as if it were continuous.

Our analysis of Hypotheses 2 and 3 is more straightforward. In these models, we are able to make full use of our panel data. A common issue arising during the analysis of longitudinal data is unobserved heterogeneity in the units under study. Unobserved heterogeneity may result in incorrect inferences concerning the magnitude and significance of individual effects. To control for heterogeneity, fixed-effects models are estimated using specification:

$$\text{Environmental Performance} = \alpha'd + \beta'x + \epsilon \quad (5)$$

where the vector d is a set of dummy variables corresponding to each facility under observation. The vector x represents our independent variables and includes *ISO 9001 Adoption*, *Maximum Inventory*, *Facility Size*, *Regulatory Stringency*, *Abatement Costs*, and *Permits*.

Analysis and Results

To test Hypothesis 1, we first estimate the link between lean production and the adoption of an environmental management standard (ISO 14001 Adoption). Model 1 presents the results of the probit specification. Because of our large sample size, we follow Leamer's recommendation to adjust the threshold level for statistical significance (Leamer 1978). Leamer's formula for accepting significance is $F_{r,n-K} > [(n-K)/r] * (n^{r/n} - 1)$, where r is the number of restrictions in the test, n is the sample size, and K is the number of coefficients that are estimated in the specification (including the intercept). For tests of the individual coefficient estimates, r equals 1. In order to calculate the t -value cutoff, we take advantage of the relationship that the square of the t distribution with x degrees of freedom equals the F distribution with 1, x degrees of freedom.

For our full sample, we find evidence that ISO 9001 Adoption predicts future ISO 14001

Adoption (Table 3). To control for possible industry fixed effects (e.g., average inventory levels or the relative rate of ISO adoption), we added dummy variables for each four-digit sic code to Model 2. Four-digit sic codes that have no firms that have adopted ISO 14001 must be removed from the sample. For this more limited sample, we find a similar result that just fails to meet the Leamer significance cutoff (standard error: $2.88 < 2.98$). Thus we find moderate support that lean production facilitates the adoption of environmental management practices (Hypothesis 1). Model 2 presents the results of our two-staged model. For parsimony, only the second stage results are presented. (See Table 4, Model 6 for an estimation of the first stage.) We find evidence that ISO 9001 adopters are more likely to adopt ISO 14001.

Together, the two models provide moderate evidence that ISO 9001 leads to ISO 14001. We believe, however, that this evidence should be interpreted cautiously. We find no evidence that Maximum Inventory has an impact on ISO 14001 Adoption. This lack of a relationship is perhaps not surprising since ISO 14001 closely parallels the ISO 9001 standard. The lack of evidence for Maximum Inventory may suggest that adoption of one standard makes it easier to adopt another, not that experience with lean production encourages the adoption of environmental management standards. Alternatively, it might suggest that innovativeness or some other ability causes facilities to adopt standards quickly.

To estimate Hypothesis 2 (lean production leads to lower waste generation and lower onsite waste treatment), we estimate future relative waste generation levels among establishments across the entire time period 1991-1996. Lagging the independent variables 1 year helps in analyzing causality, and it corrects for potential contemporaneous events that might jointly influence independent and dependent variables. We use a fixed effects analysis to correct for any constant facility characteristics that might jointly influence both independent and dependent variables. We find that facilities that are ISO 9001 certified generate significantly less waste (Table 4, Model 3). We also find evidence that facilities that have lower maximum inventory levels generate less waste (Table 4, Model 3). We do not find that firms

TABLE 3
Adoption of Environmental Management Standard (ISO 14001)

	Probit Model 1	Probit Model† 2	2SLS Model 3
ISO 9001 Adoption	0.440* (0.107)	0.368 (0.128)	0.019* (0.004)
Maximum inventory	0.045 (0.019)	0.051 (0.025)	-0.002 (0.001)
Controls			
Relative emissions	-0.009 (0.031)	-0.012 (0.037)	0.019 (0.008)
Facility size	0.146* (0.023)	0.114* (0.031)	0.003* (0.001)
Firm ISO 14001 adopters	0.090* (0.011)	0.079* (0.009)	0.017* (0.000)
Industry ISO 14001 adopters	0.025* (0.005)	1.748* (0.21)	0.001* (0.000)
Constant	-3.477* (0.150)	-6.79* (0.518)	-0.003 (0.006)
n	17,499	8324 [‡]	17,499
χ^2 Stat	622.06*	637.42*	
F statistic			949.80*
R ² (pseudo for probit model)	0.277	0.330	0.225

Standard errors are presented in parentheses. * t -Value of estimate exceeds Leamer's suggested t -value (3.13 in Models 1 and 3, 2.99 in Model 2). † Includes industry fixed effect dummy variables. Because some 4-digit SIC codes have no ISO 14001 members, it removes these SIC codes from the analysis.

TABLE 4
Estimates of Environmental Performance 1987–1996

	Waste Generation ($t + 1$) 3	Onsite Treatment ($t + 1$) 4	Total Emissions ($t + 1$) 5	Relative Emissions ($t + 1$) 6
ISO 9001 Adoption	-0.055* (0.015)	-0.012 (0.016)	-0.254* (0.032)	-0.031 (0.016)
Maximum inventory	0.034* (0.003)	0.004 (0.004)	0.074* (0.007)	0.028* (0.003)
Controls				
Facility size	-0.058* (0.005)	0.007 (0.006)	0.052* (0.011)	-0.041* (0.006)
Regulatory stringency	-2.266* (0.286)	-0.641 (0.312)	-8.730* (0.596)	-1.159* (0.307)
Abatement costs	-0.000* (0.000)	-0.000 (0.000)	-0.001* (0.000)	-0.000 (0.000)
Permits	-0.023* (0.008)	-0.026 (0.009)	-0.132* (0.017)	-0.006 (0.009)
Constant	0.770* (0.057)	0.109 (0.062)	3.875* (0.118)	0.452* (0.061)
n	68,813	68,813	68,813	68,813
Number of facilities	17,499	17,499	17,499	17,499
F Stat	57.09*	4.15*	114.39*	23.56*
R ²	0.7713	0.7954	0.8953	0.7883

Facility fixed effect dummies are included but not presented in all models. Standard errors are presented in parentheses. * t -Value of estimate exceeds Leamer's suggested t -value (2.88 in all models).

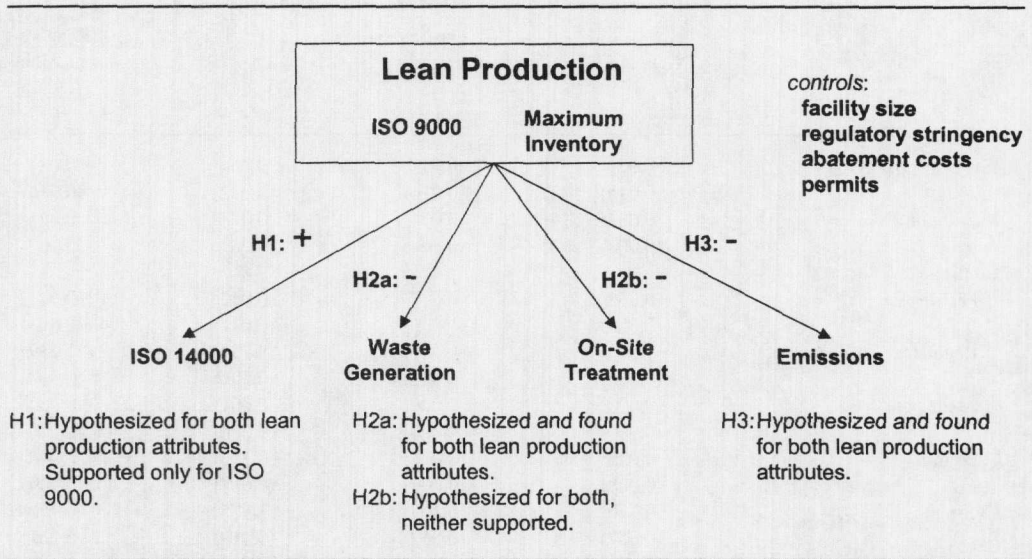
that adopt ISO 9001 or that have lower maximum inventory levels treat less waste onsite (Table 4, Model 4). Thus we do not support the later half of Hypothesis 2 that establishments that adopt lean production systems engage in less onsite treatment.

Finally, we use a fixed effect analysis to determine the net effect of lean production on pollution (Hypothesis 3). We find that firms that have adopted ISO 9001 have significantly lower total emissions (Table 4, Model 5). In addition, we find that the smaller a plant's maximum inventory, the lower are its total emissions. In other words, we find support that establishments that adopt lean production practices, both in terms of quality management and lower inventory, have lower emissions (Hypothesis 3). Of course, Total Emissions is a crude measure of environmental performance. Although we include facility size and control for fixed facility effects, we still do not fully capture the possibility that firms of different size in different industries face different production functions. Recall that Relative Emissions measures an establishment's emissions relative to its industry given its size. Regressing Relative Emissions on our independent variables, we find that facilities with less inventory have lower Relative Emissions (Table 4, Model 6). The coefficient of ISO 9001 has the expected sign but is below our stringent test of significance (Table 5).

Conclusions

In this paper, we propose that lean production is complementary to environmental performance. We propose that adoption of lean production may lower the marginal cost of pollution reduction. We show that adoption of ISO 9001 increases the likelihood that managers will adopt the ISO 14001 environmental management standard. We also show that lean production is associated with greater source reduction (pollution prevention). Finally, we show that the net effect of these changes in managerial behavior is that lean production is associated with lower emissions. Hence, we find empirical support for the assertion that "lean is green."

TABLE 5
Summary of Findings



Our research highlights the importance of existing capabilities in determining managers' propensity to adopt new management practices and begins to uncover the extent to which these practices must be related. Cohen and Levinthal (1990) argue that existing capabilities allow managers to better understand and absorb new technologies. Scholars have inferred that firms may thus tend to develop along tracks of technological experience (Dosi 1982; Teece 1988). Iansiti (2000) suggests that experience allows managers to engage in "parallel experimentation" and may allow the firm to better envision new relationships between technology and markets. Our research suggests that technologically related experience (lean production and source reduction) may allow the firm to move in surprisingly different performance domains (quality improvement and environmental performance).

Future research is needed to unpack the nature of the relationship between lean and green. We are unable to discern whether lean production (1) reduces the cost of implementing pollution reduction or (2) reduces the cost of finding new opportunities for profitable operational improvement (of which pollution reduction is one). The distinction is important to theories of profitable greening. If lean production influences search costs, it would suggest that opportunities for profitable greening might go unexploited until other activities reveal these opportunities to managers. If, however, lean production reduces the cost of implementing pollution reduction measures, it would suggest that the value of pollution reduction is contingent on the previous adoption of complementary practices such as lean production.

Finally, our findings further support the idea that potential complementarities exist among operational practices, and that firms should consequently consider adopting these practices in bundles (MacDuffie 1995; Milgrom and Roberts 1995). MacDuffie (1995) argues that when firms move to lean production, they should adopt a bundle of new inventory, technology, and work practices. Our research suggests that managers should consider including green practices in this bundle.¹

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