Measuring Long-term Effects of the Fukushima Daiichi Nuclear Power Plant Accident on Real Estate Prices

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Abstract The Fukushima Daiichi Nuclear Power Plant accident was caused by the Great East Japan Earthquake in March, 2011. Widespread areas in eastern Japan were contaminated by the huge release of radioactive materials. We analyze the long-term effects of the accident on land prices by estimating the hedonic equation with regional fixed effects. Our estimation results show that the soil contamination by cesium-134/137 affected the surrounding land prices negatively; however, this effect disappeared after only one year. This implies that we should discreetly interpret the results in estimating the cost of the Fukushima nuclear accident by the hedonic approach.

The Fukushima Daiichi Nuclear Power Plant accident was caused by the Great East Japan Earthquake and the subsequent tsunami on March 11, 2011. Widespread areas in eastern Japan were contaminated by the huge release of radioactive materials into the environment. Immediately after the accident, the national government designated "evacuation order zones," which included areas within a 20-kilometer radius of the nuclear plant, and "planned evacuation zones," where the cumulative radiation dosage may have reached as much as 20 mSv[1] after the accident. The number of evacuees due to the accident reached 164,865 people in the peak period of May 2012, and 89,319 people have been forced to evacuate over a long period as of July 2016 (Fukushima Prefecture, 2016). The Fukushima accident has had a significant impact on the Japanese economy.

According to Morishima, Sawa, and Takeuchi (2013), the Fukushima accident revealed the numerous risks of nuclear operations, including the costs involved with a nuclear accident. The accident has called into question the efficacy of energy policies in many countries. As of August 2016, most nuclear power plants in Japan have discontinued operations, and, correspondingly, the dependence on fossil fuels as an energy source has increased. The Japanese government has been forced to rethink its energy policy. Other countries have also followed similar paths; for example, Germany adopted a long-term plan to cease its operation of nuclear power plants. However, the United Kingdom decided to maintain its energy policy of reliance on nuclear power generation.

It is important to know how the Fukushima accident has caused indirect economic damage and to what extent such damage is permanent. Several previous studies examined the economic losses caused by the Fukushima accident, most via the application of a hedonic approach (Yamane, Ohgaki, and Asano, 2013; Tanaka and Managi, 2015; Kawaguchi and Yukutake, 2017). Although these studies focused on the effects of the accident in the short term, the long-term effects have not been examined adequately because insufficient time has elapsed since the accident. In this study, we analyze the long-term effect of the Fukushima accident on land prices by estimating a longer term application of hedonic land price equations. We use real estate transaction data for the Fukushima prefecture from the first quarter of 2009 to the fourth quarter of 2012.

Literature Review and Interpretation of Results from Hedonic Approach

There are a lot of previous studies that estimate the effect of externalities on properties by the hedonic price approach [see Boyle and Kiel (2001) for a review]. Recently Wisinger (2014) examines whether a different approach to the information gathering process influences the relation between the level of chemical hazard and residential prices in these sites estimated by the hedonic technique. Allen, Austin, and Swaleheen (2015), using the spatial regression model, show that there are significant price differentials among houses adjacent to highways, those near high-traffic highways, and those farther from highway on-ramps.

However few studies examine the effect of radioactive contamination on prices because of the rarity of such cases. Nelson (1981) and Gamble and Downing (1982) estimate the impact of the March 28, 1979 Three Mile Island Nuclear Generating Station accident on land prices in the surrounding areas. None of these studies finds a decrease in land prices in the surrounding areas after the accident. In particular, Nelson (1981) examines the longer term effects of the accident and confirms that the accident did not have an impact on land values in the long run.

Regarding the Fukushima accident, Yamane, Ohgaki, and Asano (2013), Tanaka and Managi (2015), and Kawaguchi and Yukutake (2017) systematically examine the property damage using a hedonic approach based on measured radioactive contamination. Yamane, Ohgaki, and Asano (2013) find that radioactive contamination caused a significant decrease in the land price evaluation by licensed real estate appraisers for property taxation. Tanaka and Managi (2015) examine the change in land prices due to the radioactive contamination from January 2011 to January 2012, and find a significant price decrease for radioactive contaminated land. Kawaguchi and Yukutake (2017), using real estate transaction data from the second quarter of 2010 to the first quarter of 2012, estimate the total land property damage to be approximately 0.13%–0.25% of Japan's GDP. These studies using the hedonic approach supply very suggestive information on the cost of nuclear power generation.

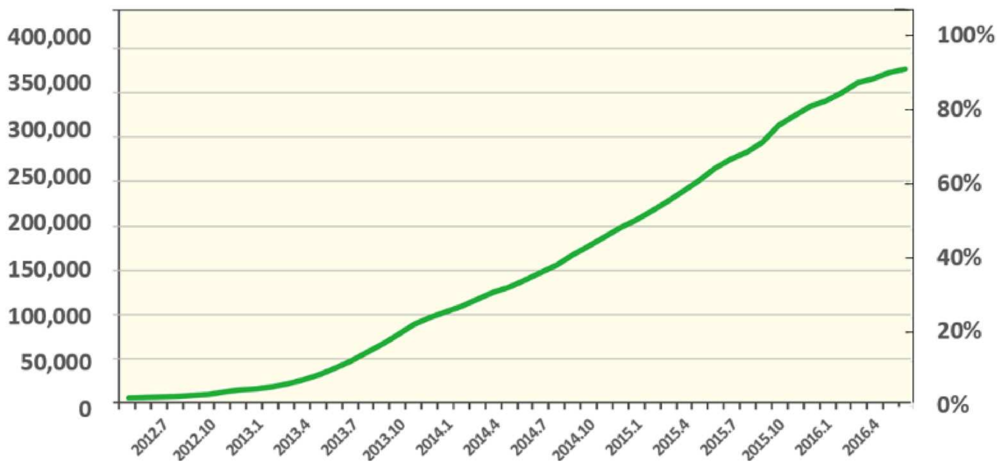
It is important to internalize external diseconomies of nuclear plant risk, that is, to calculate people's willingness to pay for radioactivity contamination applying the hedonic approach for the purpose of sustainable use of real estate close to nuclear plants. Recent studies concerning the effect of environmental quality on property prices have paid particular attention to the endogeneity caused by the correlation between the observed environmental amenities and unobserved locational characteristics.

The hedonic approach requires the assumption that any factor that impacts property values can be held constant by introducing all such possible factors into the model. Therefore, we need the complete list of variables; however, there are no such studies that could control for all the factors. In order to address this problem, some studies employ the spatial regression model (Allen, Austin, and Swaleheen, 2015), while others introduce a fixed effect term into their model (Yamane, Ohgaki, and Asano, 2013; Kawaguchi and Yukutake, 2017). Seiler (2014), showing the weakness of the hedonic approach, applies the experimental design method to measure the externality of power lines on property values.

However, despite such careful treatment for endogeneity, hedonic analysis based on short-term information in these studies sometimes causes serious problems, particularly in situations when external diseconomies are changed. Such results should be carefully interpreted for two reasons. First, all of these studies confirm the negative value effect by a comparison of the property value at multiple time points, before and after the accident. Rosen's (1974) hedonic model was considered at a time when preferences in the market were stable. Therefore, in extending the analysis at different points in time, we should impose an implicit assumption "stability over time" that is either identical preference over time or proper conditioning on changing preference (Parmeter and Pope, 2013). In such cases, we cannot directly interpret the result of the hedonic approach as the marginal willingness to pay (MWTP) for removing the contamination.

Second, the situation of the radioactive contamination keeps changing over time. The Japanese government published "the Decontamination Guideline" in December 2011, and "the Act on Special Measures (the Act on Special Measures concerning the handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District-Off the Pacific Ocean Earthquake That Occurred on March 11, 2011)" came into force in January 2012. Through the Act, the Ministry of Environment designated "special decontamination areas"[2] and "intensive contamination survey areas,[3] and decontamination was begun at the earnest. Exhibit 1 shows the progress of residential decontamination. The construction of one-half of 420,811 houses planned initially was completed in January 2015, and approximately 75% of affected residences were decontaminated by June 2016. Moreover, residents have easily been able to obtain information on the radioactive contamination over time. For example, over 3,000 monitoring posts and real-time dosimetry systems to measure spatial radiation dose were installed all over Fukushima prefecture in the year after the accident, and people were then able to know contamination information in detail. Wisinger (2014) examines whether the ways of obtaining information differentiate the impact of the externality on property prices and confirms that visual information has a strong influence on them. Therefore the installation of these systems probably does not have a small effect on the evaluation of the contamination.

Exhibit 1 | Progress of Residential Decontamination



Note: 420,811 houses are initially planned for decontamination (i.e., 100% = 420,811 houses). *Source:* the Ministry of Environment (http://josen.env.go.jp/zone/details/fukushima_progress.html).

Ganwande, Jenkins-Smith, and Yuan (2013) treat such long-term effects as an event of negative externality. They confirmed the long-run effect of incidence-free transport of nuclear waste by using Charleston County property sales data over 13 years. In this case, one event emerged, that is, the shipment of radioactive spent nuclear fuel by train. So far, no accident has happened, the situation has not changed, and the news of the shipment has also decreased. Namely there has been no update of information on the shipment. In that sense, there is a high probability that their analysis satisfies the assumption of stability over time.

In this study, we examine the time-varying effect of the Fukushima Daiichi Nuclear Power Plant accident on land values by including the interaction terms of quarterly time dummies and the contamination variable in the hedonic approach. We merge the real estate transaction data with the degree of radioactive contamination recorded one year after the accident, using a detailed geographic unit (cho or oaza), which is as detailed as the U.S. ZIP Code, as the key. We employ the geographic unit fixed effects model to allow for the correlation between the unobserved land characteristics and proximity to the nuclear power plant. Conditional on the location fixed effects, we argue that the degree of radioactive contamination in each area is randomly determined by meteorological conditions that lead to the movement of the radioactive-contaminated plume and the timing of its radioactive release. Then we can interpret the coefficients of the contamination as difference-in-differences estimators, as in Ganwande, Jenkins-Smith, and Yuan (2013). Our estimation results show that the contamination affected the land prices negatively. However, this effect did not last long and disappeared after one year. That is, the effects have changed over time. We analyze our sample for the period between the first quarter of 2009 and the fourth quarter of 2012. As shown in Exhibit 1, this did not cover the period after the beginning of the full-scale decontamination plan. Therefore, our results do not show the effect of the actual decontamination on the land price but the effect of prospective decontamination and changes in the recognition of the contamination. This implies that we should discreetly interpret the results in estimating the cost of the Fukushima Daiichi Nuclear Power Plant accident using the hedonic approach.

Data and Methods

Data

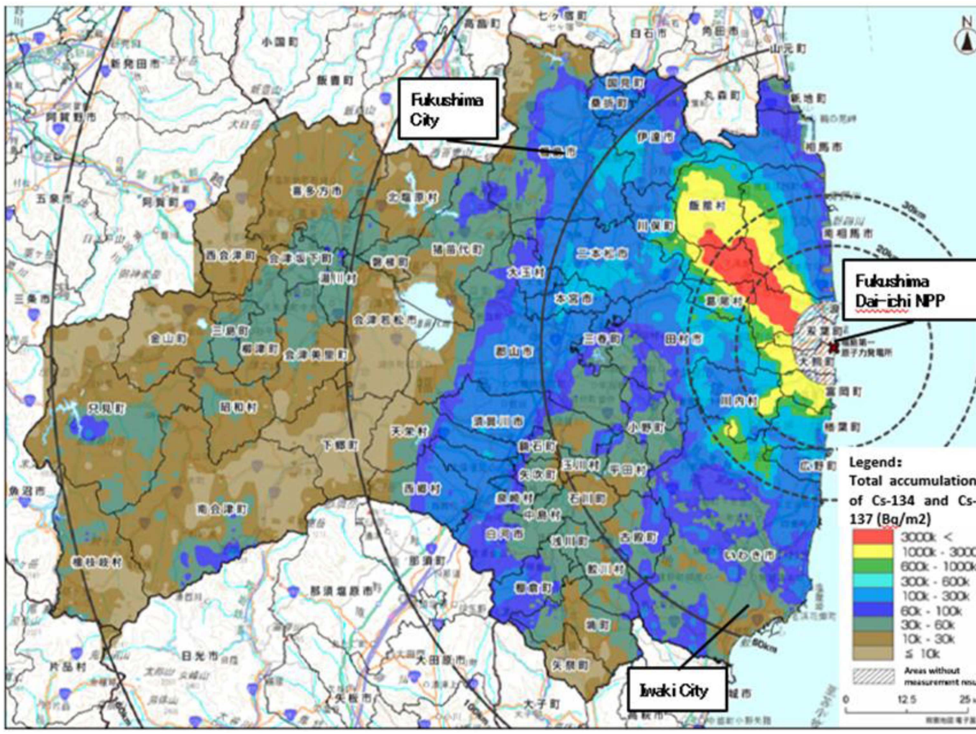
We use two sets of data to construct our sample for the estimation of the hedonic property price equation. The first set deals with real estate transactions before and after the Fukushima accident by geographic location. The second set measures the degree of radioactive contamination after the accident by geographic location.

The data source for the first set is the Land General Information System maintained by the Ministry of Land, Infrastructure, Transportation and Tourism in Japan. The ministry sends a survey to all the new owners of real estate registered with the regional Legal Affairs Bureau. The timing of transactions is recorded on a quarterly basis. Because a unique identification number for each property has not been disclosed, we cannot construct property-level panel data and analyze by the repeat sales method. Thus, we obtained the micro data of each transaction from the Ministry's website. We use this sample for observations from the Fukushima prefecture between the first quarter of 2009 and the fourth quarter of 2012.

The survey includes information on the attributes of each transacted real estate, for instance, the location, price, area, and shape of the land, the width of the facing road, regulations on land use, and the name of and distance to the nearest railway station or bus stop. We use the price per square meter of land as the dependent variable and the attributes of the land as the independent variables.

The second data source is the airborne survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. Exhibit 2 shows the monitoring results that show the degree of soil contamination by cesium-134 and cesium-137 per square meter (unit: kBq),[4] as of August 28, 2011 [see Yoshida and Kanda (2012) for a brief explanation]. We can obtain continuous data, which consists of radioactive cesium deposition densities at the median points of the quarter grid squares (approximately 250 m x 250 m) defined by JIS X 0410. We use the data as of May 31, 2012.[5] We match the grid data and the transaction data using geographic information system (GIS) software and identify the most prevalent degree of contamination within detailed geographic units (cho and oaza) in terms of land area. These geographic units[6] are a subdivision of local municipalities. The distribution of radioactivity is determined by not only the distance from the nuclear plant, but also the meteorological conditions just after the explosion of the reactor covers. A series of explosions affected different regions depending on the movement of plumes and precipitation.

Exhibit 2 | Total Accumulation of Cesium-134 and Cesium-137 on the Ground Surface in Fukushima Prefecture, as of August 28, 2011



Source: Ministry of Education, Culture, Sports, Science and Technology (http://radioactivity.nsr.go.jp/en/contents/4000/3168/24/1270_0912_2.pdf).

Two meteorological events were particularly important in determining soil contamination: the precipitation on March 15 in the northwest and western areas of the plant, which intensely contaminated the areas; and the precipitation on March 21 that contaminated the area 200 km south of the plant (Mathieu et al., 2012; Yoshida and Takahashi, 2012). Although the distribution of the radioactive contamination used in this study is the one published in May 2012, the media started reporting a similar map as early as a month after the accident, in April 2011. (The distribution of the radioactive contamination shown in Exhibit 2 is the one published in August 2011.) The U.S. National Nuclear Security Administration, for example, published monitoring results around Fukushima Daiichi on April 3, 2011 that are similar to those published by the Japanese government in November 2011.

Other than such maps, people can obtain information daily on the spatial radiation dose rate of principal cities and towns from newspapers and TV programs. Especially, in Fukushima prefecture, over 3,000 monitoring posts and real-time dosimetry systems to measure spatial radiation dose have been installed on schools, kindergartens, hospitals, and other public spaces since February 2012, in addition to conventional monitoring posts. The monitoring data are available from the monitoring posts, as well as via a website of Fukushima prefecture (http://fukushima-radioactivity.jp/pc/) in real time since April 2012. Furthermore, local governments in Fukushima prefecture distributed integrating dosimeters to 280,000 people (children up to junior high school and pregnant women) in the summer of 2011. People can even buy a simple dosimeter via the Internet for around USD 100. In such situations, people can easily obtain information on the radioactivity in real time. We therefore assume that consumers started reacting to information about the contamination immediately after the accident.

We match the transaction data with the radioactive fallout data using geographic units (cho and oaza) as the key variables. The data include 7,529 land transactions from 1,274 geographic units. Exhibit 3 reports the descriptive statistics of the sample.

In the heavier contaminated areas, there is a possibility that radioactive contamination affects not only the land value but also the amount of land transactions. Exhibit 4 shows the number of transactions by the degree of radioactive contamination every three months. The total number of transactions decreased sharply in all categories at the time of the accident in 2011:Q1; however, it recovered immediately after the accident. Especially, a sharp increase is observed after 2012:Q2. This trend is probably due to the reconstruction demand. However, the recovery trend is weak in the heavier contaminated areas. The more contaminated the land was after the accident, the fewer transactions that took place on it.

We next examine the change in prices of transacted land. Exhibit 5 displays the land price per square meter by the degree of radioactive contamination. An increase in radioactive contamination is generally associated with a decrease in land price. The aggregate average land price shows that the land price decreased sharply just after the accident and has not recovered to the level in the pre-accident period. The less contaminated areas show virtually no change between the pre- and post-accident periods with the exception of 2011:Q3. In the heavier-contaminated areas, land prices decreased sharply compared with the aggregate price, but recovered quickly. Prices reached the pre-accident level in 2012:Q1.

These exhibits show that the degree of radioactive contamination is negatively associated with both the number of transactions and land prices. These findings suggest that radioactive contamination of land depreciates the value of residential land. The rough tabulation, however, prevents us from identifying the causal impact of radioactive contamination on the value of residential land and its effect over time, as we do not control for the change in land attributes between the pre- and post-accident periods.

Hedonic Approach

We model the natural logarithm of land price per square meter as determined by the following hedonic price equation:

Exhibit 3 | Descriptive Statistics

	Mean	Std. Dev.	Min.	Max.
Dependent Variable				
Transaction price: yen / m^2	25,319.03	19,735.20	1.52	363,636.40
Independent Variables				
Cesium 134/137: kBq / m^2	206.96	648.84	5.00	20,000.00
Distance from the nuclear plant: km	60.95	21.12	3.00	166.60
Size of land: m^2	580.62	1,602.23	13.2	71,250
Width of facing road: m	6.71	4.17	0	60
Distance to the nearest station: km	43.15	32.56	0.5	120
Types of Land Shape				
Almost square or rectangular	0.08	0.28	0	1
Almost square	0.06	0.24	0	1
Almost trapezoid	0.11	0.31	0	1
Almost rectangular	0.28	0.45	0	1
Square	0.01	0.11	0	1
Not facing road	0.01	0.08	0	1
Trapezoid	0.04	0.20	0	1
Rectangular	0.22	0.41	0	1
Irregular shape	0.18	0.39	0	1
Land Use Regulation				
Residential area	0.52	0.50	0	1
Commercial area	0.07	0.26	0	1
Manufacturing area	0.09	0.28	0	1
Other purpose area	0.32	0.47	0	1
Time Dummy				
Q1_2009	0.050	0.217	0	1
Q2_2009	0.047	0.211	0	1
Q3_2009	0.054	0.225	0	1
Q4_2009	0.064	0.245	0	1
Q1_2010	0.067	0.250	0	1
Q2_2010	0.062	0.242	0	1
Q3_2010	0.061	0.240	0	1
Q4_2010	0.059	0.235	0	1
Q1_2011	0.024	0.152	0	1
Q2_2011	0.076	0.265	0	1
Q3_2011	0.047	0.211	0	1
Q4_2011	0.064	0.245	0	1
Q1_2012	0.060	0.238	0	1
Q2_2012	0.072	0.259	0	1
Q3_2012	0.089	0.285	0	1
Q4_2012	0.105	0.306	0	1

Note: For residential land, $N = 7{,}529$.

Exhibit 4 | Change in the Numbers of Transactions by the Degree of Contamination (2009:Q1 = 0.0%)

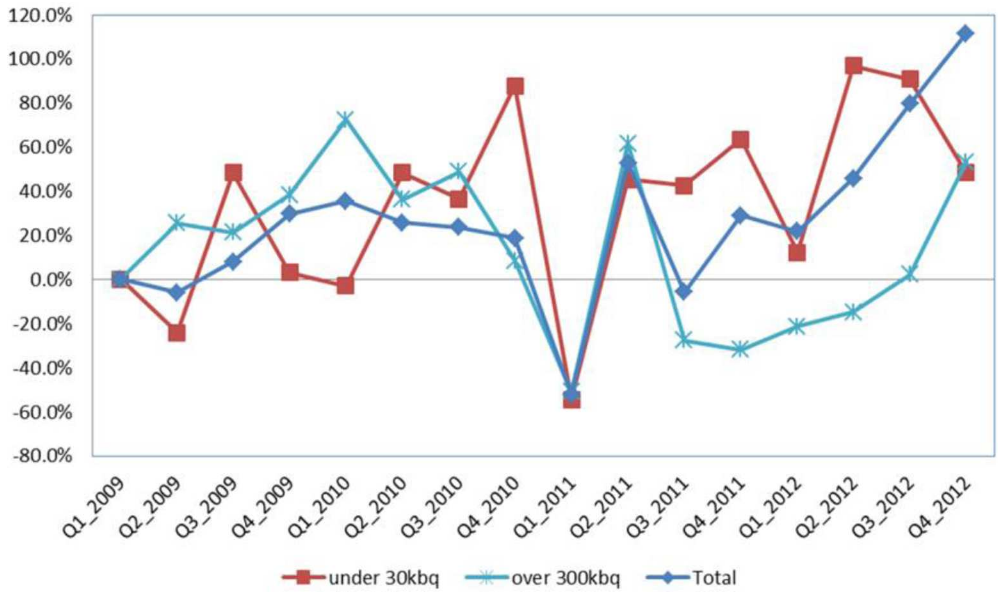
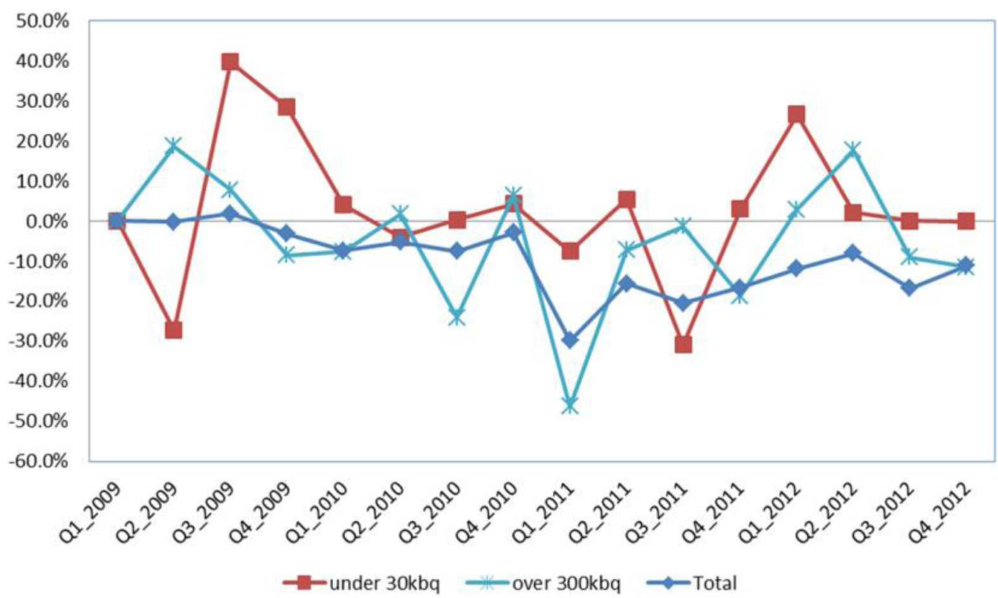


Exhibit 5 | Change in the Land Transaction Prices/m^2 by the Degree of Contamination (2009:Q1 = 0.0%)



$$lnp_{ijt} = \alpha + \sum_{t=q2\_2011}^{q4\_2012} \beta_t D_t lnCs_j + \sum_{t=q2\_2011}^{q4\_2012} \eta_t D_t lndistance_j + \sum_{t=q1\_2009}^{q4\_2012} \delta_t D_t + X_{it}\gamma + a_j + u_{ijt}, \quad (1)$$

where i is the index for a transaction; j is the index for the regional unit (cho or oaza); t is the index for the quarter; P_{ijt} is the transacted price of land per square meter; D_t is the year quarter dummy variable for post-accident transactions; Cs_j is the radioactive contamination level in the post-accident period; $distance_j$ is the distance from the Fukushima Daiichi Nuclear Power Plant; X_{it} is the vector of dummy variables for land attributes, including the shape of land, the regulation on land use, size of land, width of facing road, and distance from the nearest station to the property; a_j is the time-invariant unobserved characteristics of region j (1,274 geographic units); and u_{ijt} is the idiosyncratic disturbance.

In the hedonic model, we assume a log-log relation between the two dependent variables—the degree of contamination and the distance from the Fukushima Daiichi Nuclear Power Plant—and the price of land. Using the price logarithm as a dependent variable is desirable because a change in the explanatory variable has a proportional effect on the pre-accident price, and it is indeed widely used in the literature (Boyle and Kiel, 2001). Our sample includes areas that were almost unaffected by contamination even after the accident. The level of contamination is observed as zero in such areas, which is the same level as before the accident. Since the zero observations cannot be converted to logarithmic form, we replaced them as a median of 5,000 bq between 0 and 10,000 bq, which is a minimum detectable value, and then transformed them to logarithmic form. In fact, a small amount of cesium contamination existed even before the Fukushima accident due to atmospheric nuclear tests in the 1960s.[7] This operation does not cause any problems in the results.

The key identifying assumption of our estimation is the non-correlation of $lnCs_j$ and u_{ijt}, conditional on other covariates and regional fixed effects. The geographic spread of the radioactive fallout after a power plant failure is almost entirely dependent on the timing of the explosion of the structures that cover the nuclear reactors and the meteorological conditions around the time of the event, as suggested by several simulation studies (Mathieu et al., 2012; Yoshida and Takahashi, 2012). The movement of the radioactive plume and precipitation after the accident were major determinants of the geographic distribution of radioactive contamination, although these meteorological conditions hardly affected the residential land value through pathways other than radioactive contamination of the land. Therefore, we believe that the post-accident degrees of contamination and the time-variant regional shocks are not systematically correlated.

Similarly, we assume that there is no correlation between $lndistance_j$ and u_{ijt} because the equation is conditioned on the regional fixed effects. The correlation between the distance from the nuclear plant and the time-invariant region-specific price component apparently is negative. The densely contaminated area close to the power plant was priced lower even in the pre-accident period. Poor rural local municipalities accepted the nuclear power plant with the hope of local job creation and an increase in tax revenue (Ando, 2015). The negative correlation by the endogenous location can be eliminated by estimating the model with fixed effects estimation.

Under these assumptions, the coefficients of $D_t lnCs_j$ and $D_t lndistance_j$ in Equation (1) can be interpreted as DID estimates, as with the analysis in Gawande, Jenkins-Smith, and Yuan (2013). Our data includes observations after the accident in 15 municipalities that were not designated as "special decontamination areas" or "intensive contamination survey areas." Since such observations exist in the areas that satisfy the radiation regulation before the accident (under 1 mSV per year), they can be interpreted as the control group and are about 11% of the observations after the accident.

Estimation Results

Estimation Results for the Hedonic Function

Column (1) of Exhibit 6 reports the hedonic regression results of residential land price on the logarithm of distance from the Fukushima Daiichi Nuclear Power Plant and the other characteristics of land. In this model, the variable of distance contains no information on the proximity to the plant itself, but has information on the degree of contamination as a proxy variable, because we control regional fixed effects excluding the case when the effect of proximity changes over time. The coefficients for the interaction term of the logarithm of distance from the nuclear plant and the quarter time dummy variable between the first and fourth quarter of 2011 are estimated to be positive but statistically insignificant. These results indicate that the distance from the plant does not serve as the proxy variable for the contamination, as anticipated. After the first quarter of 2012, the coefficients are estimated to be negative and even significant for *Q3_2012* and *Q4_2012*. The estimated coefficient, −0.343, implies that a 1% increase in the distance decreases the residential land price by 0.343%. Namely, the closer the land to the nuclear plant, the higher the evaluation of the land.

The coefficients for the other independent variables are quite standard. The coefficient of scale of the site area has a positive and significant effect on the land price. The land near a station or facing a wide road has a high evaluation. An irregular shape of the land decreases its price. While being designated as a commercial area increases the price, the land, which is designated as a manufacturing area or others, has a lower price.

Column (2) of Exhibit 6 shows the hedonic regression results that replaced the logarithm of distance with the logarithm radioactive fallout. The coefficients for the interaction term of the logarithm of contamination and the quarter time dummy variable are estimated to be significant between the second quarter of 2011 and

Exhibit 6 | Estimation Results for the Hedonic Function (*Q1_2009–Q4_2012*)

Variables	(1)	(2)	(3)	Variables	(1)	(2)	(3)
Time dummy × log distance (Base category: Before accident)				Time dummy × log Cesium 134/137 (Base category: Before accident)			
Q1_2011	0.094		0.058	*Q1_2011*		−0.039	−0.037
	(0.247)		(0.253)			(0.071)	(0.072)
Q2_2011	0.169		0.079	*Q2_2011*		−0.132**	−0.127**
	(0.172)		(0.180)			(0.061)	(0.064)
Q3_2011	0.053		−0.041	*Q3_2011*		−0.121**	−0.126**
	(0.148)		(0.149)			(0.048)	(0.049)
Q4_2011	0.332		0.244	*Q4_2011*		−0.124**	−0.101**
	(0.403)		(0.405)			(0.060)	(0.048)
Q1_2012	−0.149		−0.201	*Q1_2012*		−0.086*	−0.099*
	(0.145)		(0.149)			(0.051)	(0.052)
Q2_2012	−0.171		−0.179	*Q2_2012*		0.015	−0.003
	(0.129)		(0.139)			(0.034)	(0.037)
Q3_2012	−0.343**		−0.383***	*Q3_2012*		−0.023	−0.052
	(0.134)		(0.133)			(0.042)	(0.041)
Q4_2012	−0.267**		−0.295***	*Q4_2012*		−0.009	−0.015
	(0.116)		(0.114)			(0.043)	(0.039)

Exhibit 6 | (continued)

Estimation Results for the Hedonic Function (*Q1_2009–Q4_2012*)

Variables	(1)	(2)	(3)	Variables	(1)	(2)	(3)
Types of land shape (Base category: Irregular shape)				Land use regulation (Base category: Residential area)			
Log size of land	−0.177***	−0.175***	−0.176***	*Commercial area*	0.108*	0.105*	0.108*
	(0.018)	(0.018)	(0.018)		(0.057)	(0.056)	(0.057)
Log width of facing road	0.090***	0.089***	0.090***	*Manufacturing area*	−0.104	−0.098	−0.104
	(0.009)	(0.009)	(0.009)		(0.071)	(0.071)	(0.071)
Log distance to station	−0.177***	−0.177***	−0.176***	*Other purpose area*	−0.981***	−0.984***	−0.978***
	(0.036)	(0.038)	(0.036)		(0.131)	(0.141)	(0.132)
Almost square or rectangular	0.157***	0.157***	0.158***	*Constant term*	11.367***	11.353***	11.352***
	(0.045)	(0.045)	(0.044)		(0.163)	(0.171)	(0.164)
Almost square	0.339***	0.336***	0.340***	*Time dummy*	Yes	Yes	Yes
	(0.044)	(0.045)	(0.045)	District F.E.	Yes	Yes	Yes
Almost trapezoid	0.151***	0.149***	0.151***	R^2	0.251	0.250	0.253
	(0.038)	(0.038)	(0.038)				
Almost rectangular	0.231***	0.230***	0.233***				
	(0.034)	(0.034)	(0.034)				
Square	0.285***	0.277***	0.282***				
	(0.060)	(0.060)	(0.059)				
Not facing road	0.053	0.065	0.066				
	(0.102)	(0.102)	(0.102)				
Trapezoid	0.196***	0.201***	0.201***				
	(0.050)	(0.050)	(0.051)				
Rectangular	0.270***	0.273***	0.273***				
	(0.039)	(0.039)	(0.039)				

Notes: The sample size is 7,529. Standard errors robust against the regional unit-level clustering are reported in parentheses.
*$p < 0.1$
**$p < 0.05$
***$p < 0.01$.

Exhibit 7 | The Result of Placebo Test (Q1_2009–Q4_2010)

Variables	Coeff.
Second term dummy × log distance from nuclear plant	0.039 (0.074)
Second term dummy × log Cesium 134/137	0.033 (0.036)
Variables of other land characteristics	Yes
Time dummy	Yes
District F.E.	Yes
R^2	0.020

Notes: The sample size is 3,490. Standard errors robust against the regional unit-level clustering are reported in parentheses.
$^{*}p < 0.1$
$^{**}p < 0.05$
$^{***}p < 0.01$.

the first quarter of 2012. However, these effects tend to decrease over time and we cannot confirm the statistical significance after *Q2_2012*. These results imply that the negative evaluation for the contamination disappeared only one year after the accident.

Column (3) of Exhibit 6 reports the results of the hedonic model that includes two types of interaction terms: (1) the terms of the distance and the time dummy variables; and (2) the terms of the contamination and the time dummy variables. All estimated coefficients are almost the same as those shown in columns (1) and (2). These results show that the distance and the contamination do not depend on each other in this specification and have different impacts on land prices. In the second quarter of 2011, a 1% increase in the contamination decreases land prices by 0.127%. However, such effects did not last long. In the first quarter of 2012, the effect decreased to 0.099% and lost statistical significance after the second quarter of 2012.[8]

Estimation Results for Placebo Regression

In this subsection, we confirm that the radioactive fallout does not affect land prices before the nuclear disaster. To implement such a placebo test, we divide the sample into two parts only using the pre-accident period (the first term: the first quarter of 2009 to the fourth quarter of 2009; the second term: the first quarter of 2010 to the fourth quarter of 2010) and examine whether the systematic difference of the price trend exists between the two groups using the same hedonic function as in the previous section. Then, the model includes two interaction terms: (1) the logarithm of the distance from the nuclear plant and the second-term dummy variable; and (2) the logarithm of contamination and the second-term dummy variable.

Exhibit 8 | Change in the Land Transaction Prices / m² in Each Region (2009:Q1 = 0.0%)

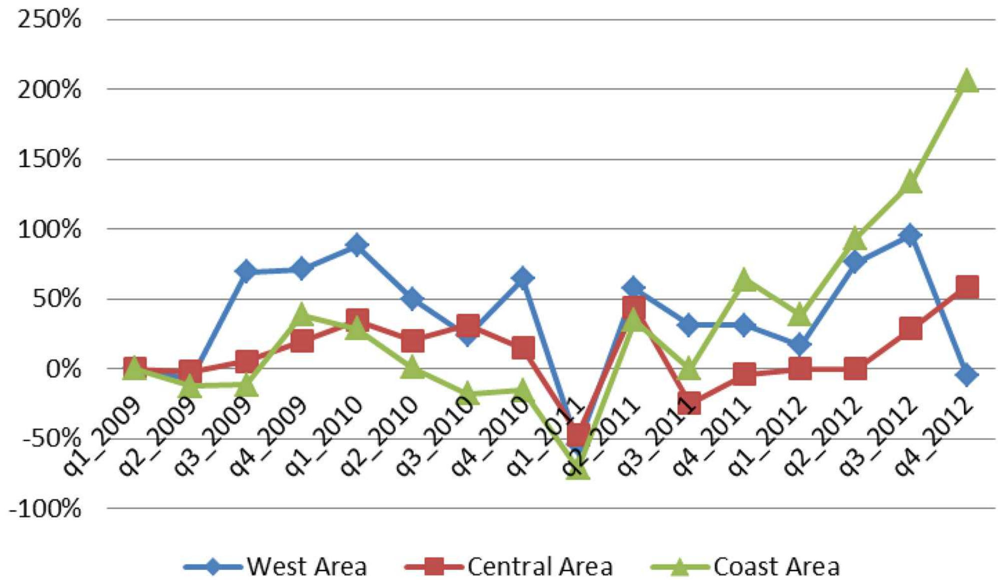


Exhibit 7 presents the results of the placebo test. The coefficients of both the interaction terms are insignificant. Therefore, the effect of radioactive contamination on the land is only observed after the accident and does not include other information in the pre-accident period.

Conclusion

In this study, we examined the time-varying effect of the Fukushima Daiichi Nuclear Power Plant accident on land values. We used hedonic price equations with detailed regional unit fixed effects and obtained the following results. First, the contamination had a negative effect on land prices. However, the effect did not last long and disappeared after only one year. Second, the distance from the nuclear plant did not have an impact on the land prices immediately after the accident. That is, the effect of distance did not decay as the distance became larger. On the contrary, after the first quarter of 2012, the coefficients are estimated to be negative and even significant for the third and fourth quarters of 2012. These results imply that properties in the neighborhoods surrounding the Fukushima Daiichi Nuclear Power Plant have higher land values. The proximity to the nuclear plant does not serve as a proxy variable of the contamination.

Furthermore, the distance and contamination variables have an independent relation in our model, since the existence of the distance variables does not affect the estimates of the contamination coefficients and vice versa. These results indicate that the degree of radioactive contamination in each area is determined not by distance from the plant but by random meteorological conditions since there are no land transactions due to residence restriction in more severely contaminated areas that are quite close to the plant and the influence of distance on the contamination relatively decreased.

It is noteworthy that the disappearance of the contamination effect at the end of 2011 and the beginning of 2012 coincided with the appearance of the distance effect in our results. These results contradict the analysis of Gawande, Jenkins-Smith, and Yuan (2012), which confirmed the lasting impact of nuclear waste shipment on property prices. The contradiction reflects a difference in the frequencies of information updating.

There was one event at the start of spent nuclear fuel shipment by train in the case of Gawande, Jenkins-Smith, and Yuan (2012), while the information continues to be updated in our analysis. For example, the government published ''the Decontamination Guideline'' and enforced ''the Act on Special Measures'' at the beginning of 2012. Through the Act, the Ministry of Environment designated ''special decontamination areas'' and ''intensive contamination survey areas.'' It began decontamination planning in more detail. Furthermore, over 3,000 monitoring posts and real-time dosimetry systems to measure the spatial radiation dosage over Fukushima prefecture are installed at almost the same time. As people obtain more accurate information on the radioactive contamination, they have been able to judge the actual influence of the radiation pollution on their health. For example, they understand what the maximum acceptable dosage level means and know how to properly deal with the contamination. Therefore, the estimation results indicate that although uncertainty still remains in the market to some extent, the prices of land have recovered from those in the panic transactions held immediately after the nuclear accident. There is a possibility that some people, especially evacuees, understood the risk even from a small amount of contamination and determined to switch from temporary evacuation to migration.

The new housing demand by evacuees from the evacuation order areas and by the reconstruction workers may be reflected in this effect. Exhibit 8 shows the transition of residential land in each region in Fukushima prefecture. The transactions of residential lands in the coastal area, where the Fukushima Daiichi Nuclear Power Plant is located, rapidly increased after the second quarter of 2012.

Our analysis is highly suggestive in estimating the cost or loss due to a nuclear power plant accident. In the traditional hedonic approach, cost due to an external diseconomy is estimated based on the MWTP in a buyer's bid. In order to apply this method, however, the model should be based on an important assumption, namely ''stability over time,'' which indicates the consumer's preference is stable at different points in time (Parmeter and Pope, 2013). The assumption is not satisfied by the time-varying effect and the cost has a severe bias. Therefore, we should discreetly interpret the cost and the MWTP by the hedonic model using a sample over multiple time periods the same as this study.[9]

Future research should consider sample selection bias in order to obtain a more accurate analysis. Exhibit 4 shows that the degree of radioactive contamination is negatively associated with the number of transactions. The contamination decreases the value of land to a point where no further transactions occur. This decrease in the volume of transactions may result in an underestimation of the land damage because the areas severely damaged were not transacted after the accident and do not appear in our sample. However, our study does show the effects over time and the dissipation of negative impacts over time of property no longer contaminated.

Endnotes

1 Millisievert is abbreviated as mSv. Sievert is the index the airborne survey of radiation effect for organisms (include humans).

2 Eleven municipalities in Fukushima prefecture were designated as special decontamination areas where the annual cumulative dose of radiation could be more than 20 mSv/y. The decontamination of these areas is being implemented by the national government.

3 The intensive contamination survey areas include 104 municipalities in 8 prefectures, where the additional exposure dose was over 1 mSv/y. Decontamination is implemented by each municipality with financial and technical support from the national government.

4 Kilobecquerel is abbreviated as kBq. Becquerel is a measurement unit of radioactivity, equal to one radioactive decay per second.

5 The areas adjacent to the Fukushima Daiichi Nuclear Power Plant are excluded from the airborne survey since the contamination of land cannot be distinguished from the direct effect of radioactive material at the plant. However, no lands have been traded in the areas.

6 For example, the postal address of The Tokyo Metropolitan Government Office is ''2-8-1 Nishi-Shinjuku, Shinjuku-ku, Tokyo.'' In this address, ''Nishi-Shinjuku'' is the cho or oaza.

7 For further details, see the website ''radioactivity.eu.com,'' created and maintained by physicists with the help of the Science Editor EDP Sciences and with the help of the Institut National de Physique Nucléaire et Physique des Particules (IN2P3), http://www.radioactivity.eu.com/site/pages/Caesium_137.htm. Accessed on March 7, 2017.

8 We also estimate the same model for longer periods from the first quarter of 2009 to the first quarter of 2015. The results are almost the same and we can confirm the existence of the time-varying effects.

9 Refer to Parmeter and Pope (2013) for further details about interpreting estimates using the hedonic approach in program evaluations, especially including samples at multiple points of time.

References

Allen, M.T., G.W. Austin, and M. Swaleheen. Measuring Highway Impacts on House Prices Using Spatial Regression. *Journal of Sustainable Real Estate*, 2015, 7:1, 83–98.

Ando, M. Dreams of Urbanization: Quantitative Case Studies on the Local Impacts of Nuclear Power Facilities using the Synthetic Control Method. *Journal of Urban Economics*, 2015, 85, 68–85.

Boyle, M.A. and K.A. Kiel. A Survey of House Price Hedonic Studies of the Impact of Environmental Externalities. *Journal of Real Estate Literature*, 2001, 9:2, 117–44.

Fukushima Prefecture. Step for Revitalization in Fukushima, 2016. http://www.pref.fukushima.lg.jp/uploaded/attachment/179983.pdf. Accessed on September 15, 2016.

Gamble, H.B. and R.H. Downing. Effects of Nuclear Power Plants on Residential Property Values. *Journal of Regional Science*, 1982, 22:4, 457–78.

Gawande, K., H. Jenkins-Smith, and M. Yuan. The Long-run Impact of Nuclear Waste Shipments on the Property Market: Evidence from a Quasi-experiment. *Journal of Environmental Economics and Management*, 2013, 65:1, 56–73.

Kawaguchi, D. and N. Yukutake. Estimating the Residential Land Damage of the Fukushima Accident. *Journal of Urban Economics*, 2017, 99, 148–60.

Mathieu, A., I. Korsakissok, D. Quelo, J. Groell, M. Tombette, D. Didier, E. Quentric, O. Saunier, J.-P. Benoit, and O. Isnard. Atmospheric Dispersion and Deposition of Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident. *Elements*, 2012, 8:3, 195–200.

Morishima, A., A. Sawa, and S. Takeuchi. Toward the Establishment of a New Compensation System for Nuclear Damages. The 21st Century Public Policy Institute Policy Proposal, 2013.

Nelson, J.P. Three Mile Island and Residential Property Values: Empirical Analysis and Policy Implications. *Land Economics*, 1981, 57:3, 363–72.

Parmeter, C.F. and J.C. Pope. Quasi-Experiments and Hedonic Property Value Methods. In: *Handbook on Experimental Economics and the Environment*, J.A. List and M.K. Price (eds.). Edward Elgar, 2013, 3–66.

Radioactivity.eu.com. http://www.radioactivity.eu.com/site/pages/Caesium_137.htm. Accessed on March 7, 2017.

Rosen, S. Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *Journal of Political Economy*, 1974, 82, 34–55.

Seiler, M. Power Lines and Perceived Home Prices: Isolating Elements of Easement Rights and Noise Pollution. *Journal of Sustainable Real Estate*, 2014, 6:1, 47–61.

Tanaka, K. and S. Managi. Impact of a Disaster on Land Price: Evidence from Fukushima Nuclear Power Plant Accident. *Singapore Economic Review*, 2016, 61:1, 1–15.

Wisinger, P. Chemical Hazardous Sites and Residential Prices: Determinants of Impact. *Journal of Sustainable Real Estate*, 2014, 6:1, 3–21.

Yamane, F., H. Ohgaki, and K. Asano. The Immediate Impact of the Fukushima Daiichi Accident on Local Property Values. *Risk Analysis*, 2013, 33:11, 2023–40.

Yoshida, N. and J. Kanda. Tracking the Fukushima Radionuclides. *Science*, 2012, 336: 6085, 1115–16.

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