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Land subsidence exposed: the impact on house prices in the Netherlands

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Abstract

Land subsidence which is primarily driven by water management practices and enhanced by increasing droughts is a growing global concern that affects the environment, infrastructure, and housing. In the Netherlands, subsidence damages houses and their foundations, resulting in high costs of repair for homeowners. However, public awareness remains limited about individual vulnerability and financial impact. This study aims to identify the link between land subsidence and house prices. Using over 100,000 housing transactions from 2000–2022 and detailed subsidence data, we find an average price discount of 2.3–5.0% for houses exposed to land subsidence, with larger effects for houses constructed before 1970 for which foundation damage is more prominent. Our findings suggest that, even with limited information and low societal urgency, homebuyers do consider the potential damage of land subsidence in expressing their willingness to pay for a house, especially after recent droughts.

Keywords: Land subsidence, Water management, House prices, Hedonic pricing, Climate adaptation
JEL-classification: Q54, R11, R14, R21, R31

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1. Introduction

Land subsidence has become a global concern particularly impacting coastal regions such as in eastern China (Ao et al., 2024) and Indonesia (Mehvar et al., 2018), where it exacerbates the impact of sea level rise, increases the vulnerability to floods, causes environmental degradation, and damages houses and infrastructure. This results in economic losses, injuries, and even deaths (Hallegatte et al., 2013; Abidin et al., 2015; Chan et al., 2021). In most cases, human practices related to water management are a major driver of subsidence (Abidin et al., 2015; Yoo and Perrings, 2017; Wade et al., 2018). In the Netherlands, for instance, centuries of peatland drainage to facilitate agriculture (Chen et al., 2023) has resulted in land subsidence of up to 2 meters, leading to current elevation levels being well below sea level (Erkens et al., 2016). One of the most affected regions is the Green Heart in the western part of the country where the groundwater levels, managed by the regional water authorities, are deliberately kept low to increase productivity in dairy farming (Stouthamer et al., 2020; Pelsma et al., 2020). While this fosters grass growth and improves the accessibility of farming vehicles (Rli, 2024), it also enhances the compaction of peat and clay, peat oxidation, and clay shrinkage, contributing to land subsidence (Van der Meulen et al., 2007; Koster et al., 2018; Fokker et al., 2019). Furthermore, these processes are likely amplified in the future (Kok and Angelova, 2020) by more frequent and severe summer droughts (Van Dorland et al., 2023).

The Dutch land subsidence case is an interesting example of a “creeping crisis” and a “wicked problem” as discussed by Van den Ende et al. (2023) as the slow pace of subsidence (around 2 millimeters per year, Erkens et al., 2016) makes this a crisis in slow motion that generates limited societal urgency. Conflicting interests and interconnected impacts make this a particularly wicked problem that has initiated a heated policy debate in the Netherlands in recent years (Van den Born et al., 2016; Rli, 2020). The higher productivity in dairy farming comes at the cost of increased flood risk due to a higher relative rise of the sea level (De Moel et al., 2011), saltwater intrusion (Van Beek et al., 2007), and water storage issues (Van den Born et al., 2016). Additionally, peat oxidation results in increased CO_2 emissions contributing to 2.5% of the total emissions of the Netherlands (Erkens et al., 2016; Van den Akker et al., 2008).

In recent years, the negative effects on homeowners have gained particular attention, relating to two specific impacts on their property and surroundings. First, land subsidence damages older houses and their foundation, particularly those built before 1970 on shallow foundations, which transfer the building's weight to surface layers composed of weak peat and clay soils. When subsidence occurs at different rates beneath the house, it can result in uneven subsidence of the foundation, leading to damage such as house tilting and cracks in the walls. In some cases, pilings were used to stabilize the foundation in deeper, more stable soil layers unaffected by subsidence. However, the subsiding soil in between can stick to the pilings, increasing the load and still posing a risk of damage. Often, these pilings were made of timber, posing an additional risk. When groundwater levels drop, which exposes the timber to oxygen, fungal and bacterial decay may set in. Over time, this weakens the pilings potentially damaging the foundation and house itself. After 1970, construction practices shifted towards using better-designed concrete pilings, that are less vulnerable to these effects (KCAF, 2022; Rli, 2024). Second, land subsidence requires costly maintenance of gardens, private parking places, public infrastructure, and local facilities (Van den Born et al., 2016). This causes direct and indirect costs, and hindrance to the residents of affected regions, concerning both older and newer houses.

Although land subsidence for long was not considered as an urgent societal issue, the summer droughts of 2018, 2019, 2020, and 2022 amplified the negative effects, leading to a substantial increase in reported foundation damage. Despite this, there remains much uncertainty about the exact costs and timing of the damage. Estimates suggest that by 2050 the total costs of foundation damage in the Netherlands may reach €60 billion (Kok and Angelova, 2020; KCAF, 2022), with infrastructure-related damage adding another €5.2 billion (Van den Born et al., 2016). However, these estimates are broad and are difficult to translate to individual homes. In extreme cases, repairing a damaged foundation may cost up to €120,000 (Van den Born et al., 2016; Kok and Angelova, 2020; Rli, 2024), but there are currently no large-scale structural surveys available on the state of maintenance for individual houses. In the absence of such information, we hypothesize that homebuyers form their own expectations of the potential damage based on, for example, visible damage at the house, damage in the surroundings, public maps, and media coverage. Van der Linden (2015) shows that experiencing the negative effects of such risks can change individual perceptions. Public awareness may also have been stimulated by initiatives to provide more public information, such as digital maps indicating neighborhoods vulnerable to land subsidence.[1] However, it remains unclear whether the increasing effects and availability of information have led to greater awareness. This study seeks to address this research gap by investigating whether the

[1] See www.klimaateffectenatlas.nl/en

impact of land subsidence over time has raised awareness among homebuyers. More awareness should manifest in price discounts for houses where damage is expected, which reflects the average perceived expectation of the damage. In a broader context, this may reveal whether information provision and experiencing the negative effects of creeping crises could heighten public awareness

Investigating the awareness among homebuyers is important, as affected homeowners currently carry the financial burden of the damage. At the moment, the repair costs are neither insurable (AFM, 2021) nor compensated. The only financial instrument available is a loan for sustainable foundation recovery, that is only available when specific requirements are met (Van Dijk and Nijboer, 2019). Besides, several factors discourage the involved parties from investigating the potential damage (AFM, 2023). First, incumbent homeowners are not obliged to disclose information to potential buyers or assess the risks, and they are unlikely to do this voluntarily, as potential damage could decrease the value of their house. Second, mortgage lenders could face a decrease in their loan-to-value ratio if they expect potential damage, requiring them to take provisions. Third, governments fear accountability and financial responsibility for the damage (Rli, 2024). As a result of this, some houses may be overvalued by homebuyers. When the damage eventually manifests, homeowners may have insufficient financial resources to repair the damage timely (AFM, 2023). As a result, repairs are postponed which worsens the damage eventually leading to dangerous situations and possibly even structural collapse (AFM, 2021). People may have to leave their homes leading to very large insecurities (Rli, 2024). On top of that, multiple health risks may arise. People are 'trapped' in their damaged homes which results in mental health issues (Saputra et al., 2019).

Several methods exist to study the awareness among homebuyers, one being the impact on house prices (Garrod and Willis, 1992). Theoretically, house prices are forward-looking and should reflect the expected damage in current prices (Glaeser et al., 2008). Some studies found varying price discounts depending on the identification of land subsidence damage (Koster and Van Ommeren, 2015; Yoo and Perrings, 2017; Yoo and Frederick, 2017; Willemsen et al., 2020; Hommes et al., 2023). However, these studies are mostly small-scale and focus on local effects. Large studies generalizing effects for entire regions have been challenging due to limited data. For example, research in Phoenix, Arizona identified only whether a house was within a subsidence zone without linking this to local subsidence rates (Yoo and Perrings, 2017; Yoo and Frederick, 2017). In the Netherlands, Willemsen et al. (2020) focused on short periods for the cities of Gouda (2016–2018) and Rotterdam (2009–2015), two cities infamous for foundation damage, during a period when the negative effects started to become more pronounced. Hommes et al. (2023) built further on this by using text mining to identify reported foundation damage in housing advertisements. Damage was reported in 2.2% of the advertisements for houses constructed before 1975, thus, their study indicates the price impact for a small group of buyers fully aware of the damage. This differs from our larger study sample, which includes all housing properties that are potentially at risk of damage. This broader dataset allows us to study the extent to which uncertain, potential damage is included in house valuations. Another challenge in these studies relates to local unobserved heterogeneity. Houses exposed to land subsidence may be located in rural areas with specific spatial qualities such as open space and natural amenities. Existing literature addresses this issue with neighborhood-fixed effects (Koster and Van Ommeren, 2015; Yoo and Perrings, 2017; Willemsen et al., 2020). However, this approach has limitations, as neighborhood-fixed effects focus on within-neighborhood variation. This may cause issues for neighborhoods with little subsidence variation and likely contributes to the between-neighborhood variation, which could bias the results (Abbott and Klaiber, 2011).

To address the limitations of these studies, we introduce several innovations in our analysis. First, we estimate a more generalized large-scale impact of land subsidence on house prices using a unique dataset that provides highly localized subsidence rates for the Green Heart. Second, we expand our analysis by looking beyond foundation damage, assessing all potential damage resulting from subsidence, for example, damage to gardens and utility cables. Third, by using housing transactions between 2000–2022, we can study whether the awareness has increased over time as people started to experience the negative effects in more recent years. Fourth, we employ a piecewise approach to examine how the rate of land subsidence affects price discounts. Finally, we address issues with local unobserved heterogeneity differently by using a (Bayesian) multilevel hedonic pricing model with varying effects, which allows for variation in the impact of land subsidence between neighborhoods. This approach is also less sensitive to outliers as it shrinks outliers toward the mean and allows for more accurate predictions in neighborhoods with limited observations (Wheeler et al., 2014).

This paper proceeds as follows: Section 2 describes the data and provides the empirical strategy we use to estimate the impact of land subsidence on house prices. We show our results in section 3 and finish with a discussion and conclusion of our findings in section 4.

2. Data & Empirical Strategy

This section describes the data and empirical strategy used in this study. We first motivate our choice of study area in subsection 2.1; being the Green Heart, a predominantly rural area in the western part of The Netherlands. Next, Subsection 2.2 provides and discusses the determinants and modeling of land subsidence, followed by a description of the housing data in Subsection 2.3. In the last subsection 2.4, we describe how we estimate the house price impact of land subsidence.

2.1. Study area

In this study, we focus on the Green Heart region in the Netherlands, a protected open space in the western part of the Netherlands. The borders of the Green Heart changed over time with more protected land being reassigned to the built environment. We use the borders defined in 2004 and derive this data from Koomen (2020). Figure 1 depicts the geographical location of the Green Heart located in the Randstad region and surrounded by the cities of Amsterdam, Rotterdam, The Hague, and Utrecht. The Green Heart is located below sea level and consists mostly of peat and clay soil. Drainage of these soils has been going on for centuries to facilitate agriculture (Cuenca and Hanssen, 2008). The region's open meadows are primarily used for dairy farming characterizing the landscape. However, current dairy farming practices are under pressure as the sector struggles to remain competitive in the global market (Janssen et al., 2022). The groundwater level is deliberately kept low to increase productivity in dairy farming (Pelsma et al., 2020), also resulting in heavy land subsidence in the Green Heart (Pelsma et al., 2020). At the same time, there is an increased pressure to extend the built-up area of the surrounding cities driven by the large housing shortage in the Netherlands, while land subsidence inflicts damage to the built environment (Van den Born et al., 2016). These conflicting interests result in tensions between water management, dairy farming, and spatial planning resulting in heated policy debates and making the Green Heart an interesting and unique region to study.

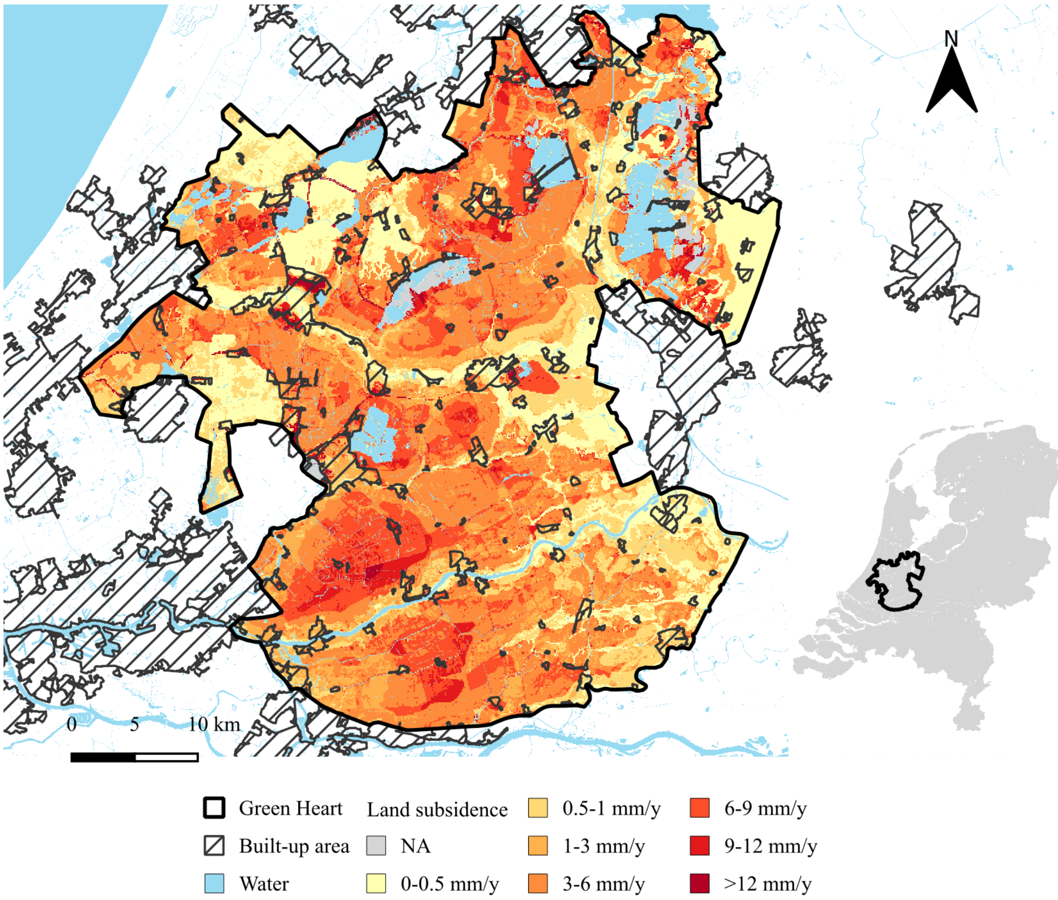

Figure 1: Land subsidence in the Green Heart region in millimeters per year (data: TNO Geological Survey of the Netherlands).

2.2. Land subsidence data

Groundwater management practices are the primary driver of land subsidence in the Green Heart. Low groundwater levels induce three processes that cause land subsidence. First, there is an outflow of groundwater in the pores of peat and clay soil, increasing the downward pressure in these soils as water also exerts an upward force. This results in the compaction of peat and clay soil. Second, peat gets exposed to oxygen initiating a combustion process that causes oxidation of the organic material inside the peat. Third, clay dries out and contracts enhancing clay shrinkage. Given these processes, the rate of land subsidence also depends on the thickness of the underlying peat and clay layers (Van der Meulen et al., 2007; Koster et al., 2018; Fokker et al., 2019). As future climate scenarios for the Netherlands predict more frequent and severe summer droughts (Van

Dorland et al., 2023), these mechanisms will likely be amplified (Kok and Angelova, 2020). TNO Geological Survey of the Netherlands uses these inputs to model future land subsidence. The model is based on a mild climate scenario and expected groundwater levels, predicting land subsidence rates at a 100 by 100-meter grid cell resolution for 2020–2050. See Van der Meulen et al. (2007), Koster et al. (2018), and Fokker et al. (2019) for a technical description of the models. These predicted subsidence rates follow a business-as-usual scenario and to a large extent replicate the past, observed subsidence rates that are the likely reference point for those that are familiar with the region. Land subsidence rates vary across the Green Heart with low subsidence rates in built-up areas and high rates over 12 millimeters per year in rural areas as depicted in Figure 1. This variation is caused by newly added anthropogenic soil layers in built-up areas that have compressed the existing peat and clay layers far below current groundwater levels. In rural areas, these layers are closer to the surface level making these areas more vulnerable to land subsidence (Koster et al., 2018).

2.3. Housing data

We utilize housing data provided by the Dutch Association of Real Estate Agents (NVM). This dataset contains about 70% of the housing transactions in the Green Heart between 2000–2022, including various housing characteristics, such as housing type, construction year, and size. We geo-locate individual houses based on their x- and y-coordinates to determine the yearly rate of land subsidence per house. House prices have increased significantly over the time span of this study. Therefore, we correct house prices with the consumer price index per year (published by CBS), using 2022 as our index year. Table 1 provides descriptive statistics of the housing data. The average house price in the Green Heart was €432,197 between 2000–2022. On average, houses experience 3.6 millimeters per year of land subsidence, but this may vary greatly by the location of a house with some houses experiencing more than 21 millimeters per year of land subsidence. 46.5% of the data consists of houses constructed before 1970. As explained previously, this group of houses is more vulnerable to foundation damage, which we will exploit in our empirical strategy.

Table 1: Variables and descriptive statistics.

Variable	Mean	SD	Min	Max
House price euros	432,197	282,265	27,078	7,971,290
Land subsidence mm/y	3.621	4.589	0.000	21.627
Size house m^2	132.022	53.570	25	750
Size lot m^2	570.309	2,379.498	20	87,305
N rooms	4.880	1.363	1	25
Terraced house	0.492	0.500	0	1
Semi-detached house	0.342	0.474	0	1
Detached house	0.165	0.371	0	1
Garden	0.780	0.414	0	1
Maintenance quality house (1 = good)	0.850	0.358	0	1
Construction year <1905	0.076	0.265	0	1
Construction year 1906–1930	0.105	0.307	0	1
Construction year 1931–1944	0.059	0.235	0	1
Construction year 1945–1959	0.058	0.234	0	1
Construction year 1960–1970	0.167	0.373	0	1
Construction year 1971–1980	0.198	0.399	0	1
Construction year 1981–1990	0.156	0.363	0	1
Construction year 1991–2000	0.124	0.330	0	1
Construction year 2001–2010	0.039	0.195	0	1
Construction year 2011–2020	0.017	0.130	0	1
Construction year 2021–2030	0.0004	0.021	0	1
N	101,452			

2.4. Empirical strategy

In this study, we estimate the impact of land subsidence on house prices. Similar to prior studies (Koster and Van Ommeren, 2015; Yoo and Perrings, 2017; Yoo and Frederick, 2017; Willemsen et al., 2020), we use a hedonic pricing model developed by Rosen (1974). The hedonic pricing method explains house prices by examining housing characteristics. Each characteristic provides the marginal effect on the house price. We model the rate of land subsidence as a housing characteristic representing a disamenity. Hommes et al. (2023) used information about foundation damage reported in advertisements to identify subsidence damage to the house. We do not have access to such information in our dataset. Therefore, we make specific assumptions to identify which houses will likely experience land subsidence damage. Willemsen et al. (2020) followed a similar approach by tracking house subsidence itself, but not the actual damage. To do so, we exploit the NVM housing data. First, prior literature shows that houses built before 1970 are more vulnerable to foundation damage (KCAF, 2022). Second, the costs vary by housing type. Terraced houses share a common foundation that legally requires all homeowners to agree on repairing the foundation. This also means that the homeowners share the costs resulting in lower overall costs (Rli, 2024). Based on these assumptions, we look at the price discounts of houses constructed before 1970 and compare these to the price discounts of houses constructed after 1970, differentiated by housing type.

There are three ways in which home buyers can form an expectation about the costs of land subsidence damage. First, land subsidence damage may be directly observed or known by the buyer, for instance, cracks are visible in the walls, the house is tilting, or information about damages might be known from the advertisement or damage reports. Second, land subsidence damage might indirectly be expected based on the surroundings and the neighborhood in which the house is located. Land subsidence damage might be visible at other similar houses in the neighborhood and roads could be subsiding. Third, homeowners can form expectations based on other information sources, such as consulting land subsidence maps, frequent media attention in specific neighborhoods, and information about the building year of the house and foundation type. To precisely assess what we measure when we find a negative impact of land subsidence, we adopt the model of Bosker et al. (2019) for the impact of flood risk and apply this to land subsidence. We first denote the price of a house i as $p_i(H, S_i)$, where H_i is a set of individual housing characteristics and S_i indicates whether a house is exposed to land subsidence ($S_i = 1$) or not ($S_i = 0$). This is in line with previous literature stating that the amount of land subsidence matters less to house damage compared to the variation in land subsidence on a very local scale (Rli, 2024; Willemsen et al., 2020). If the land subsidence is spatially very homogeneous, then the damage is usually rather minimal. Nonetheless, literature (see, e.g. Willemsen et al., 2020; Ao et al., 2024) usually models 3 millimeters per year subsidence as a threshold level. Below, we adopt a flexible specification to test this threshold level. Using this, we specify the negative impact of land subsidence ($S_i = 1$) by adopting the following model:

$$\delta = \frac{1}{I} \sum_i \left[\rho(S_i) \left[1 - \nu_i(\bar{S}_i, \tau) \right] \left(\frac{\sum_k U^H_{h_{ik}} h_{ik}}{U^X_{iX}} \right) \frac{1}{p_i(H_i, 0)} \right] \tag{1}$$

Here, δ is the parameter of interest representing the average willingness to pay to avoid the costs of land subsidence damage (in house price percentages). I are all housing transactions in the Green Heart. $\rho(S_i)$ indicates the perception by a household that a house i is exposed to land subsidence ($S_i = 1$). $\left[1 - \nu_i(\bar{S}_i, \tau)\right]$ represents the expected share of housing consumption left after land subsidence indeed takes place. If no damage is expected, then $\left[1 - \nu_i(\bar{S}_i, \tau)\right] = 1$, and total housing consumption is expected to remain unchanged after land subsidence. Expected losses from land subsidence depend on land subsidence damages actually occurring $\bar{S}_i$ and expected damage compensation by insurance or the government τ. Moreover, the expected damage is house-specific as well. Houses that are built after 1970 or have already experienced land subsidence damage and have been repaired afterward face less expected costs of damages than houses built before 1970. And as explained above, the type of houses, such as terraced or detached houses also matter for damage expectations. The third term represents the marginal utility of each housing characteristic h_{ik} divided by the marginal utility of non-housing consumption X for household i. This shows the household's preferences for each housing characteristic compared to all other consumption goods not related to housing.

Thus, we postulate that a statistically insignificant impact of δ can relate to three arguments. First, households might incorrectly infer that their house is not exposed to land subsidence ($S_i = 0$). Second, home buyers may think they will not incur any land subsidence damage because they do not see any damage in the surrounding area, or they expect that land subsidence damage will be fully compensated by insurance or the government. The latter two arguments both indicate that $\left[\nu_i(\bar{S}_i, \tau)\right] = 0$. Third, δ increases in the relative importance of housing consumption versus non-housing consumption, in other words, an insignificant impact indicates that home buyers do not care about land subsidence damage and prefer to spend their money on other goods.

Furthermore, current studies indicate issues with local unobserved heterogeneity (Koster and Van Ommeren, 2015; Yoo and Perrings, 2017; Yoo and Frederick, 2017; Willemsen et al., 2020). Land subsidence rates are higher in rural areas, which also have specific spatial qualities such as open space and natural amenities. Adding neighborhood-fixed effects is a common way to address these issues, however, this approach has some limitations. Fixed effects only estimate the impact within a neighborhood. This becomes problematic when certain neighborhoods experience relatively homogeneous land subsidence rates potentially leading to biased estimates (Abbott and Klaiber, 2011). To overcome this problem, we estimate our hedonic pricing specification with a (Bayesian) multilevel model including varying effects. The varying effects allow for variation in the impact of land subsidence on house prices between different neighborhoods. Another advantage of this approach is less overfitting of the data. The model essentially provides more accurate estimates for neighborhoods with few observations and shrinks outliers toward the mean (Wheeler et al., 2014). This yields the following specification:

$$
\begin{aligned}
P_{itz} &\sim N(\mu_{itz}, \sigma^2) \\
\log \mu_{itz} &= \delta S_{itz} + \gamma S_{itz} \times C_{itz} + \beta H_{itz} + \theta_t + \eta_z \\
\eta_z &\sim N(0, \sigma_z^2)
\end{aligned} \tag{2}
$$

Here, we specify the model in two levels. First, we assume the transaction price P for house i at time t in neighborhood z is normally distributed with mean μ_{itz} and variance σ^2. We take the log of mean μ_{itz} and use this as our dependent variable for the hedonic pricing specification. As our second level, we include varying effects η_z for neighborhoods z, which we assume to be normally distributed with mean 0 and variance σ_z^2. δ is the parameter of interest representing the average willingness to pay to avoid the costs of land subsidence damage, where S_{itz} is a set of bins representing different land subsidence bandwidths for household i in year t in neighborhood z. This piecewise approach allows us to control for nonlinear effects in land subsidence, where our main specification uses 0–0.5 millimeters of land subsidence per year as the reference category. Table 4 in the appendix shows the descriptive statistics per land subsidence bin, which indicates that the housing characteristics are relatively equal across different bins. We interact the different land subsidence classes S with a dummy variable C equal to 1 when a house was constructed after 1970. δ then captures the effect of land subsidence for houses constructed before 1970. H represents a set of housing characteristics, such as size, housing type, and construction year. House price trends vary over time, therefore, we add time-fixed effects θ to control for yearly and monthly changes in house prices. Note that this does not capture the effect of inflation as we have already corrected the house prices with the consumer price index with 2022 as the base year.

3. Results

This section provides the results of our study. We first show the baseline results in subsection 3.1, followed by the impact over time in subsection 3.2. Next, subsection 3.3 shows several robustness checks.

Table 2: baseline results.

	Dependent variable: Log house price					
	Basic models		Interaction construction year >1970			
Land subsidence bins	(1) Simple model	(2) Prefered model	(3) All Houses	(4) Terraced	(5) Semi-detached	(6) Detached
0.5–1 mm/y	−0.106***	−0.004	−0.009**	−0.003	−0.029***	−0.024**
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.009)
1–3 mm/y	−0.120***	−0.023***	−0.026***	−0.011*	−0.043***	−0.047***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.007)	(0.014)
3–6 mm/y	−0.091***	−0.050***	−0.084***	−0.048***	−0.058***	−0.093***
	(0.003)	(0.003)	(0.004)	(0.006)	(0.007)	(0.011)
6–9 mm/y	−0.070***	−0.025***	−0.045***	−0.026***	−0.024**	−0.063***
	(0.003)	(0.003)	(0.005)	(0.007)	(0.008)	(0.011)
9–12 mm/y	−0.101***	−0.047***	−0.063***	−0.032***	−0.050***	−0.071***
	(0.005)	(0.004)	(0.006)	(0.008)	(0.010)	(0.015)
>12 mm/y	−0.063***	−0.024***	−0.039***	−0.021**	−0.040***	−0.052***
	(0.004)	(0.004)	(0.006)	(0.007)	(0.008)	(0.014)
0.5–1 mm/y * year >1970			0.013**	−0.002	0.011	0.022
			(0.005)	(0.005)	(0.006)	(0.013)
1–3 mm/y * year >1970			0.012*	0.011	0.031***	0.045*
			(0.006)	(0.006)	(0.009)	(0.017)
3–6 mm/y * year >1970			0.058***	0.044***	0.034***	0.039**
			(0.005)	(0.006)	(0.008)	(0.013)
6–9 mm/y * year >1970			0.037***	0.012	−0.000	0.058***
			(0.005)	(0.008)	(0.009)	(0.014)
9–12 mm/y * year >1970			0.030***	0.025**	0.018	0.018
			(0.008)	(0.009)	(0.011)	(0.020)
>12 mm/y * year >1970			0.030***	0.004	0.030***	0.038*
			(0.007)	(0.007)	(0.009)	(0.017)
Housing characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Varying effects	No	Yes	Yes	Yes	Yes	Yes
Looic	162,010	119,095	119,006	−14,294	20,422	41,590
N	101,452	101,436	101,436	49,957	34,717	16,762
R^2	0.706	0.811	0.811	0.773	0.772	0.740

Note: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

3.1. Baseline results

We show our main results in Table 2. Column (1) indicates a simple model with controls for relevant housing characteristics and time-fixed effects. The estimates show a price discount of 6.3–12.0% for houses exposed to land subsidence. This model does not control for location characteristics. We control for this by adding varying effects in column (2), which is the preferred estimation model and the main finding of this study. This results in a smaller impact of 2.3–5.0% implying that land subsidence is correlated with location characteristics. Given that the mean house price in our data is equal to €432,197, this results in an average price discount between €9,941–21,610.

In the empirical strategy, we discussed that we approach foundation damage by looking at houses constructed before 1970 for different housing types. In column (3), we investigate the average price discount for all houses. We interact the different land subsidence bins with a dummy variable equal to 1 when a house was constructed after 1970 while controlling for construction decades of a house to ensure we do not capture age effects. This makes the interpretation of the coefficients easier as the coefficients of the different land subsidence classes show the impact for houses constructed before 1970 and the interaction term shows the impact for houses constructed after 1970. The results show an average price discount of 2.6–8.4% for all houses constructed before 1970. Note that we do not consider the first class of 0.5-1 mm/y land subsidence as we will later show in the robustness check that land subsidence effects only become significant around 3 mm/y onwards. If we look at the impact for different housing types, we see in column (4) that the impact for terraced houses constructed before 1970 is equal to 1.1–4.8%. The price discount for semi-detached houses constructed before 1970 in column (5) is slightly larger at 2.9–5.8%. We find the largest impact for detached houses in column (6). This results in a price discount of 2.4–9.3% for houses constructed before 1970. Notice that there is still a negative price discount for all types of houses constructed after 1970, although much smaller than for houses constructed before 1970. Even though we use a piecewise approach with different land subsidence bins to control for nonlinear impacts, the results do not show a larger impact for higher land subsidence rates. This finding holds for all housing types.

3.2. Awareness over time

Reported foundation damage, and consequently public information provision and media attention about land subsidence have increased over time after several summer droughts. Van der Linden (2015) shows that experience with the negative impacts also results in more engagement and awareness. We investigate whether these developments have also led to higher price discounts for houses exposed to land subsidence in more recent years. Figure 2 shows the impact over time. We interact the transaction year of a house with a dummy variable indicating whether a house is exposed to land subsidence. Interacting land subsidence by transaction year results in fewer observations per year compared to pooling all data. We previously showed that the impact of land subsidence is not linearly related. Hence, we choose a threshold value of 3 mm/y to indicate whether a house is exposed to land subsidence, based on prior literature that used this as a threshold

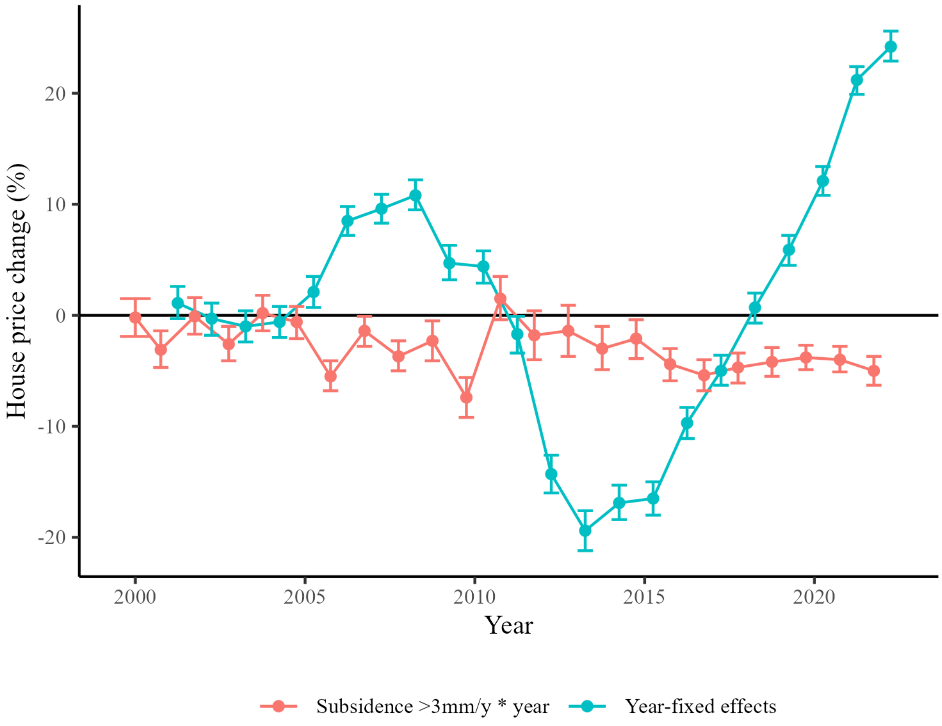

Figure 2: House price discount rates over time.

value (Willemsen et al., 2020; Ao et al., 2024). We control for business cycle effects by adding year-fixed effects. This line clearly shows a sharp decline in house prices after the financial crisis of 2008 and a sharp rise in house prices from 2015 onward. Before 2015, we hardly see any significantly negative impacts of land subsidence. However, the interaction effect indicates a consistent negative impact after 2015. This indicates that people have started considering the potential costs of land subsidence damage slightly more in recent years.

3.3. Robustness checks

We perform three additional robustness checks to investigate whether our findings are consistent. First, in our baseline estimates, we use the 0–0.5 mm/y land subsidence bin as the reference category. We test different upper boundary values to determine if this affects the estimates. Table 5 in the appendix shows that increasing the upper boundary has no large effect. The house price impact of land subsidence remains negative, with

Table 3: Results Bayesian vs OLS models.

	Dependent variable: Log house price			
	Basic models		Interaction year >1970	
	(1) BRM	(2) OLS	(3) BRM	(4) OLS
0.5–1 mm/y	−0.004	−0.001	−0.009**	−0.003
	(0.003)	(0.006)	(0.003)	(0.008)
1–3 mm/y	−0.023***	−0.015*	−0.026***	−0.019
	(0.004)	(0.008)	(0.005)	(0.010)
3–6 mm/y	−0.050***	−0.023***	−0.084***	−0.046***
	(0.003)	(0.007)	(0.004)	(0.011)
6–9 mm/y	−0.025***	−0.028***	−0.045***	−0.033**
	(0.003)	(0.008)	(0.005)	(0.011)
9–12 mm/y	−0.047***	−0.022**	−0.063***	−0.033**
	(0.004)	(0.009)	(0.006)	(0.012)
>12 mm/y	−0.024***	−0.019*	−0.039***	−0.028*
	(0.004)	(0.008)	(0.006)	(0.011)
0.5–1 mm/y * year >1970			0.013**	0.002
			(0.005)	(0.007)
1–3 mm/y * year >1970			0.012*	0.010
			(0.006)	(0.009)
3–6 mm/y * year >1970			0.058***	0.037***
			(0.005)	(0.009)
6–9 mm/y * year >1970			0.037***	0.011
			(0.005)	(0.009)
9–12 mm/y * year >1970			0.030***	0.020*
			(0.008)	(0.010)
>12 mm/y * year >1970			0.030***	0.017
			(0.007)	(0.009)
Housing characteristics	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes
Varying effects	Yes	No	Yes	No
Neighborhood-fixed effects	No	Yes	No	Yes
Looic	119,095		119,006	
N	101,436	101,436	101,436	101,436
R^2	0.811	0.863	0.811	0.863

Note: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. BRM = Bayesian Regression Model. OLS = Ordinary Least Squares.

price discounts between 1.2–5.0% across all reference bins.

Second, the baseline estimates use an interaction term to separate effects for houses constructed before and after 1970. We also test this by splitting the data into two samples. Because the year 1970 is no hard transition for the use of deep foundations with concrete piles, we choose two samples of houses constructed before 1960 and after 1980. This yields similar results to our baseline estimations.

Third, and finally, this study uses a Bayesian multilevel model with varying effects. To assess its validity, we estimate the same specification with OLS including neighborhood-fixed effects instead of varying effects shown in Table 3. Column (1) shows the preferred specification estimated with the Bayesian model. If we estimate the same specification with an OLS model with neighborhood-fixed effects in column (2), we observe a smaller price discount range of 1.9–2.8%. We also find a lower price discount for the specification with an interaction for houses constructed after 1970. If we compare the Bayesian model in column (3) with the OLS model in column (4), we now only observe a price discount range of 2.8–4.6%. Although both models estimate a negative impact of land subsidence, the OLS estimates are smaller. This arguably points to the fixed effects absorbing some of the variation in the impact of land subsidence between neighborhoods.

4. Discussion & Conclusion

This study provides new insights into the impact of land subsidence on house prices by employing a (Bayesian) multilevel hedonic pricing model. For the Green Heart in the Netherlands, we find a significant negative impact, with an average price discount between 2.3–5.0%. These effects are larger for detached houses and houses constructed before 1970, for which foundation damage is more prevalent. Moreover, our results show that the awareness of land subsidence and its impact has increased over time, particularly after people experienced the negative effects during multiple recent summer droughts.

Our findings align with the existing literature, showing a similar impact to Willemsen et al. (2020) who use a comparable approach. However, we observe a smaller average price discount than Hommes et al. (2023), which likely stems from differences in methodological approaches and the type of damage being assessed. Hommes et al. (2023) focuses on reported foundation damage in advertisements, which involves full disclosure of potential damage and addresses the most expensive type of damage. In contrast, our study compares similar houses in subsidence zones to houses in unaffected zones and captures homebuyers' perceived expectations of various types of damage, including foundation damage, sinking gardens, damage to utility cables, and issues with the sewage system. As a consequence, our observed price discount reflects a perceived expectation of damage rather than actual future damage. This broader approach may explain the smaller impact. When we focus on houses constructed before 1970, where foundation damage is more prevalent, we observe a maximum discount of 8.4%. This is closer to the 12% found by Hommes et al. (2023) for houses with reported foundation damage. This suggests that homebuyers form a reasonable expectation of the damage, even without full information.

A key contribution of this study is its focus on how homebuyers perceive the risk of land subsidence damage, emphasizing the role of expectations rather than reported damage. Homebuyers can form these expectations in various ways: by accessing publicly available subsidence data, observing visible signs of damage in the house or neighborhood, or being influenced by media coverage and historical damage. Since land subsidence does not always result in immediate or observable damage, perceived expectations of future damage are critical for understanding the price discount for affected houses. We estimate an average price discount between €9,941–21,610 per affected house, reflecting the expected costs rather than the actual future damage, which is likely higher. Besides, some houses could have already suffered and repaired damage, potentially even resulting in a premium (Hommes et al., 2023). Overall, our findings suggest that public awareness of subsidence damage, and consequently its impact on house prices, has been increasing over time, especially after people experienced the negative effects of the summer droughts. Linking these effects to the theoretical model we adopted from Bosker et al. (2019), we show three key insights that hold simultaneously. First, homebuyers often correctly identify houses exposed to land subsidence. Second, they form some expectation about the potential costs, even if this is not equal to the actual costs. Third, they take potential damage seriously and feel some urgency to take this into account.

Furthermore, we performed several robustness checks. First, we tested whether the rate of land subsidence influences the price discount. Similar to Willemsen et al. (2020), we find no such effect, it is rather the variation in subsidence beneath the house that may cause uneven subsidence of the foundation. This may even result in damage at low rates. Second, we split our data into two samples to focus on foundation damage, which yielded similar results. Third, we addressed issues with local unobserved heterogeneity differently than the current literature that mostly employs neighborhood-fixed effects (Koster and Van Ommeren, 2015; Yoo and Perrings, 2017; Willemsen et al., 2020). We opt for a Bayesian multilevel model with varying effects, as fixed effects may absorb part of the impact of land subsidence between neighborhoods. This may be particularly problematic in areas with limited observations or little variation in subsidence rates. Our results show that the price discount is larger when using varying effects compared to the fixed-effects OLS model, suggesting that fixed effects may underestimate the impact.

The findings of this study have important policy implications, particularly in the context of groundwater management. Homebuyers in areas exposed to land subsidence already anticipate considerable damage, however, they do not typically benefit from groundwater management practices that could exacerbate this damage. As summer droughts might become more frequent and severe, which likely amplify the process responsible for land subsidence, both the damage and price discounts may grow. Increasing public awareness could play an important role in shaping future policies, emphasizing the importance of public information provision about the damage and costs. As more people experience the negative effects, greater public engagement (Van der Linden, 2015) may influence policy debates, especially when considering the social costs and benefits of groundwater management. Policies that focus on sustainable practices, such as structurally increasing groundwater levels and adopting alternative forms of agriculture like paludiculture, could become more viable (Kløve et al., 2017).

This study opens several directions for further research. While we focused on the perceived expectation of potential damage, an important next step would be to monitor actual damage on a large scale to examine whether these perceived costs align with realized outcomes. Our study addresses a key research gap by examining whether the growing impact of land subsidence over time stimulates greater awareness among homebuyers. We show that homebuyers already anticipate some of the damage, and this effect has been increasing over time. As experiences with subsidence-related damage grow and public information provision improves, further research could explore how this trend evolves and continues affecting price dynamics in the long run.

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A. Appendix

Table 4: Mean by land subsidence classes conditional on neighborhoods.

Land subsidence class mm/y	0–0.5	0.5–1	1–3	3–6	6–9	9–12	>12
House price	622,262	540,130	558,376	572,078	598,946	607,428	551,805
Size	156.853	150.514	149.785	150.755	156.786	152.793	148.909
Lot size	1,809.362	1,832.177	1,933.001	2,070.398	1,996.635	2,161.915	879.633
Rooms	5.253	5.087	4.988	5.084	5.186	5.088	5.095
Terraced	0.251	0.286	0.299	0.304	0.257	0.279	0.264
Semi-detached	0.327	0.323	0.280	0.264	0.253	0.297	0.362
Detached	0.423	0.391	0.421	0.432	0.490	0.424	0.374
Garden	0.727	0.729	0.760	0.726	0.736	0.774	0.736
maintenance (good)	0.793	0.798	0.827	0.824	0.800	0.783	0.833
Construction year <1906	0.185	0.151	0.098	0.116	0.127	0.114	0.140
Construction year 1906–1930	0.139	0.136	0.100	0.102	0.117	0.139	0.159
Construction year 1931–1944	0.058	0.059	0.053	0.047	0.081	0.042	0.075
Construction year 1945–1959	0.076	0.089	0.051	0.057	0.066	0.071	0.046
Construction year 1960–1970	0.136	0.155	0.158	0.119	0.105	0.153	0.089
Construction year 1971–1980	0.141	0.149	0.196	0.194	0.196	0.171	0.188
Construction year 1981–1990	0.094	0.098	0.140	0.116	0.118	0.104	0.112
Construction year 1991–2000	0.090	0.082	0.107	0.146	0.101	0.136	0.108
Construction year 2001–2010	0.058	0.048	0.061	0.079	0.073	0.058	0.051
Construction year 2011–2020	0.023	0.026	0.032	0.022	0.015	0.010	0.018
Construction year 2021–2030	0.0004	0.0068	0.0008	0.0008	0.0003	0.0000	0.0124
Observations	26,546	22,540	13,675	15,096	10,088	5,650	7,857

Table 5: Testing different reference categories for land subsidence.

	Dependent variable: Log house price			
	(1)	(2)	(3)	(4)
Threshold	< 0.001 mm/y	< 0.5 mm/y	< 1 mm/y	< 3 mm/y
Subsidence 0.001–0.5 mm/y	0.054***			
	(0.004)			
Subsidence 0.5–1 mm/y	0.004	−0.004		
	(0.003)	(0.003)		
Subsidence 1–3 mm/y	−0.012**	−0.023***	−0.021***	
	(0.004)	(0.004)	(0.003)	
Subsidence 3–6 mm/y	−0.039***	−0.050***	−0.049***	−0.043***
	(0.003)	(0.003)	(0.003)	(0.003)
Subsidence 6–9 mm/y	−0.012***	−0.025***	−0.023***	−0.018***
	(0.003)	(0.003)	(0.003)	(0.003)
Subsidence 9–12 mm/y	−0.035***	−0.047***	−0.046***	−0.040***
	(0.004)	(0.004)	(0.004)	(0.004)
Subsidence >12 mm/y	−0.013**	−0.024***	−0.023***	−0.018***
	(0.004)	(0.004)	(0.004)	(0.004)
Housing characteristics	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes
Varying effects	Yes	Yes	Yes	Yes
Looic	118, 950	119, 096	119, 106	119, 141
Observations	101, 436	101, 436	101, 436	101, 436
R^2	0.811	0.811	0.811	0.811

Note: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.