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Abstract

Since Basel II was introduced in 2008, two approaches to calculating bank capital requirements have co-existed: lenders' internal models, and a less risk-sensitive standardised approach. Using a unique dataset covering 7 million UK mortgages for 2005–15, and novel identification, we provide empirical evidence that the differences between these approaches cause lenders to specialise. This leads to systemic concentration of high-risk mortgages in lenders with less sophisticated risk management. Our results have broad implications for the design of the international bank capital framework.

Key words: Capital regulation, banking, mortgages, specialisation, risk-taking, Basel II.

JEL classification: G01, G21, G28.

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One of the dilemmas in bank regulation is how to link capital requirements to risk. The first Basel agreement (1988) set capital requirements in proportion to risk metrics known as "risk weights". Initially, these were set by regulators. To link capital more closely to banks' own risk estimates, the Basel II agreement (2004) allowed lenders to use their internal models to calculate risk weights.[1] More recently, growing concerns about risk weights – their pro-cyclicality, excessive variability, heterogeneity, and accuracy of risk measurement – have led to proposals, such as the leverage ratio, to reduce the link between capital requirements and risk weights, as well as to reform risk weights. This paper has broad implications for those ongoing policy debates.

Risk weights vary for two reasons: risk, and the methodology used to set risk weights. Different methodologies for setting risk weights co-exist in the same market under Basel II. The "internal ratings based" (IRB) approach, as the use of internal models is more formally known, is costly to set up and manage. So while most of the largest lenders have adopted IRB, smaller banks tend to rely on the simple metrics set by regulators, formally known as the "standardised approach" (SA). Internal models also differ between lenders. Repullo and Suarez (2004) theorised that methodology-driven heterogeneity would affect how lenders compete against each other, and which risks they take, as they specialise in the assets for which their risk weights give them a comparative advantage.[2] This specialisation mechanism is related to, but distinct from, the mismeasurement of risk[3] or the procyclicality of capital requirements.

This paper empirically studies the effects of methodology-driven heterogeneity in risk weights on market outcomes: prices, portfolio composition, and the distribution of risk across lenders. We take risk weights as given, and do not attempt to assess how effectively different methodologies capture risk.[4] The residential owner-occupied mortgage market is our laboratory. This market was at the epicentre of the 2008-09 financial crisis (Besley, Meads, and Surico, 2012; Mian and Sufi, 2015), and represents a large share of total bank lending in many countries (Jordà, Schularick, and Taylor, 2016).[5] Moreover, there is evidence of substantial methodology-driven variation in mortgage risk weights (Basel Committee on Banking Supervision, 2016b).[6]

Our results show that the introduction of internal models has induced specialisation and concentration of credit risk in the UK mortgage market. Behn, Haselmann, and Wachtel (2016) provided empirical evidence that this mechanism is at work in the German corporate loan market[7], but this

[1] Internal models are used to estimate risk components such as probabilities of default and loss given default, which then are used as inputs in the risk weight functions (hard-wired in regulation).

[2] See also Rime (2005), Feess and Hege (2004), Ruthenberg and Landskroner (2008), Gropp, Hakenes, and Schnabel (2011). Calem and Follain (2007) estimated the potential impact of the introduction of IRB models in the US mortage market.

[3] If multiple lenders have different risk weights for the same risk, at least one must have mismeasured risk.

[4] This has been extensively analysed in recent contributions including Acharya and Steffen (2015), Acharya, Schnabl, and Suarez (2013), Basel Committee on Banking Supervision (2016b), Behn, Haselmann, and Vig (2014), Mariathasan and Merrouche (2014), Berg and Koziol (2016)).

[5] In the UK, mortgages account for 64% of the stock of lending to the real economy, and 74% of household liabilities. Source: UK Office of National Statistics

[6] Credit risk accounts for the majority (77%) of the variation in risk weights among IRB lenders (Basel Committee on Banking Supervision (2013)).

[7] They find not only that banks with internal models reduce loan supply more than SA lenders in response to credit risk shocks, but also that they do so less for lower risk borrowers, consistent with their comparative advantage.

has not been empirically tested for mortgages, to the best of our knowledge.[8] Specifically, IRB lenders gain a comparative advantage in capital requirements compared to SA lenders, particularly at low loan-to-value (LTV) ratios. This comparative advantage is reflected in prices and quantities. *Ceteris paribus*, we expect all lenders to price lower for lower LTV mortgages. But under Basel II versus I, IRB lenders did so by 31 basis points (bp) more, and increased the relative share of low-LTV lending in their portfolios by 11 percentage points (pp) more, than SA lenders. Such specialisation leads to systemic concentration of high risk (high LTV) mortgages in lenders who tend to have less sophisticated risk management.[9]

Methodology-driven heterogeneity in risk weights among IRB lenders, which we observe for 2009-2015, is also reflected in prices: a 1pp reduction in risk weights causes a 1bp reduction in interest rates. With an average 30 percentage point gap between IRB and SA risk weights for LTV ratios below 50%, this corresponds to an economically significant price advantage of 30bp. From the perspective of a typical borrower at this LTV level, with a 50% LTV mortgage against a £200,000 property, repayable over a remaining 15 year term, 30bp translates to around £170 per year or 0.7% of median household disposable income.[10] From the lender's perspective, a 30bp disadvantage translates to several places in 'best buy' tables, and thus likely material loss of market share.[11] If instead of risk weights we consider directly the variation in capital requirements, which is driven by both risk weights and lender-specific capital ratio requirements, a 1pp reduction in capital requirements causes a 6bp decrease in interest rates. These latter results can also be interpreted as 'pass-through' rates from lender-specific changes in risk weights or capital requirements to prices, subject to limits on external validity due to the Lucas critique. Finally, we find that the pass-through from capital requirements to prices is significant only when lenders have low capital buffers (the surplus of capital resources over all regulatory requirements). Lenders with a buffer below 6pp of risk-weighted assets increase prices by 1.7bp basis point for a 1pp increase in risk weights.

Our unique dataset joins several confidential regulatory databases, including specially collected data on average risk weights by lender, year, and LTV ratio. It contains loan-level data on approximately 7 million mortgages originated between 2005 Q2 and 2015 Q4 in the UK. Interest rates, and product and borrower characteristics, are drawn from the Financial Conduct Authority's Product

[8] Campbell, Ramadorai, and Ranish (2015) assess the effect of changes in regulatory risk weights (standardised approach) on a large Indian mortgage lender, and find evidence of a decrease in interest rates for similar risk following a reduction in risk weights for lower LTV mortgage.Basten and Koch (2015) do not find any effect of risk weights on mortgage pricing following an increase in regulatory capital (application of countercyclical capital buffers), but they do not have risk weight data for IRB lenders.

[9] The ability to obtain IRB permission can be seen as an indicator of risk modelling sophistication (See Rime (2005)).

[10] We use the most recent available figures at the time of writing, from the UK Official of National Statistics. The average UK house price was £217,888 as of September 2016 (median not available). The median household disposable income was £25,700 for the financial year ending 2015. We conservatively assume interest rates of 1% with and 1.3% without the price advantage, reflecting the level of two-year fixed rates at the time of writing. The pound amount would be higher with mortgage rates at historically more typical levels.

[11] For example, on 15 November 2016, among offers from a popular online mortgage supermarket with at least 95% market coverage (http://moneyfacts.co.uk/mortgages/mortgage-calculator/), among two-year fixed-rate mortgage products advertised to lenders with an LTV ratio of 50%, ranked by total amount repayable over two years, the initial interest rates on the first- and tenth- ranked were 0.99% and 1.19% respectively, giving a price gap of 20bp.

Sales Database (PSD); as used in, for example, Best, Cloyne, Ilzetzki, and Kleven (2015) and Uluc and Wieladek (2015). Lender-specific capital requirements and resources are drawn from the PRA's Historical Regulatory Database (De Ramon, Francis, and Milonas, 2016), and CRD-IV regulatory collections. For robustness checks, we match our main dataset to loan-level arrears data for a subsample of 1.3 million mortgages, from 2010 and 2011 FCA/CML snapshots as used in Butterworth, Fennell, Latsi, et al. (2015).

We use the within-lender variation, with more disaggregated microdata, to achieve tighter identification than was possible in earlier literature based on lender-level aggregates (eg Gambacorta (2008); Brooke, Bush, Edwards, Ellis, Francis, Harimohan, Neiss, and Siegert (2015); Michelangeli and Sette (2016); Cohen and Scatigna (2015)). In particular, by differencing or by implementing fixed effects we can more completely control for important confounders varying at lender level that are likely to be important drivers of prices, for example funding cost and average risk profile (Kashyap and Stein, 2000; Jiménez, Ongena, Peydró, and Saurina, 2014; Behn et al., 2016). With lender-level data, these factors must be controlled explicitly (eg including a measure of funding cost as a regressor to control for funding costs), which limits the quality of control in the face of potential measurement error and non-linear effects.

To overcome the identification challenges associated with lender-level data, for the German corporate loan market Behn et al. (2014) and Behn et al. (2016) use loan-level data in the spirit of Khwaja and Mian (2008), but adapted to the context of risk weights. However, their identification strategies depend on comparing the prices of different loans made to the same borrower on the same security.[12] With mortgages there is usually only one loan per property.[13]

We develop two complementary identification strategies that work with a single loan per borrower, while still largely addressing the limitations associated with identification based on lender-level data. In common with the literature for corporate loans, we use *within*-lender variation, so that we can completely control for lender-level confounders, observed and unobserved. Our identification strategies could also help improve identification in other markets where a single loan per borrower is the norm (and borrower-time fixed effects would eliminate too much of the relevant variation), so long as i) capital requirements vary within lender, and ii) within-lender variation in priced product and borrower characteristics are observed and so can be explicitly controlled. This includes many classes of retail lending (eg credit cards, personal loans, auto loans) and small business lending.

The variation in risk weights used for identification occurs along three dimensions: lender, time, and LTV ratio. The existence of risk weight variation between LTV bands within each lender allows us to control for anything that varies at the lender-time level, but is fixed within lender in a given period (funding costs, for example), and still have variation remaining for identification. The

[12] The variation in capital requirements then comes from different loans being held in different portfolios (whether at the same or a different lender) subject to different capital requirements. This approach almost completely controls for demand side effects and borrower-specific credit risk.

[13] Any further loans, known as second-charge mortgages in the UK, are i) quite different products, so not necessarily comparable in terms of demand-side effects; and ii) are subordinated rather than *pari passu*, so not comparable in terms of risk.

variation in two of these dimensions – lender and LTV ratios – is illustrated in Figure 1, using a snapshot from 2015.

[Place Figure 1 about here]

IRB risk weights increase with the LTV ratio, the main indicator for credit risk used by UK mortgage lenders.[14] In contrast, SA risk weights are fixed at 35% for LTV ratios up to 80%, and are then 75% on incremental balances above the 80% LTV threshold. IRB risk weights tend to be lower than SA risk weights across most LTV ratios, but the gap is larger for lower LTV ratios. In 2015, the gap between the average IRB risk weight and the SA risk weight was about 30 percentage points for LTV ratios below 50%, compared to less than 15 percentage points for LTV ratios above 80%. The scale of variation in risk weights between IRB lenders is smaller than the gap between the IRB average and SA risk weights, at least at lower LTV ratios.

The biggest challenge to overcome in identifying the causal effects of risk weights lies in isolating methodology-driven variation in risk weights from risk-driven variation. This is important because risk is also priced through other channels besides risk weights. We achieve this separation in two complementary ways. Each exploits a different part of the total methodology-driven variation in risk weights, and thus addresses a slightly different question. The first approach exploits the regime change from Basel I to II and uses a regression triple-difference estimator. The question addressed is, "Did Basel II cause specialisation?" The second approach exploits methodology driven variation in risk weights within the Basel II regime, using a regression specification with pairwise-interacted fixed effects and actual risk weight data. The question addressed is, "What is the effect on prices of changes to risk weights within Basel II?"

Our first approach to identification exploits the switch from Basel I to II, which produces large, sudden, and heterogeneous variation in risk weights that we interpret as quasi-experimental. Under Basel I, mortgage risk weights were completely homogeneous: a uniform 50% on every residential mortgage originated by every bank and buiding society. At the introduction of Basel II, lenders had to choose between applying to their supervisor for IRB permissions or using SA. As shown in Figure 2, both groups of lenders experienced large average decreases in risk weights, but the decreases were considerably larger for IRB lenders.[15] And, within the IRB and SA groups, the decrease in risk weights is larger for low LTV ratios, here defined as an LTV ratio equal to or less than 75%.[16]

[Place Figure 2 about here]

[14] In the UK, lenders offer mortgages with a non-linear price schedule, showing interest rate jumps at specific LTV ratios (see for example Best et al. (2015)). In other words, the interest rate is associated with a maximum LTV ratio. In this paper, we will use the terms LTV ratio and LTV band interchangeably.

[15] The apparent staged decrease in average IRB risk weights in Figure 2, with risk weights in 2008Q1-Q2 dropping only part-way to their longer run level, is an artefact arising from only having data on risk weights for a small subset of IRB lenders in that quarter. One of these lenders adopted IRB models with a delay relative to other lenders, and the another which reported temporarily and idiosyncratically high IRB risk weights for this time period.

[16] This threshold is ultimately arbitrary, but is widely used in product segmentation and in securitisation. The story told here, and our regression results, are qualitatively unchanged for 70% or 80% thresholds.

The sudden drop in risk weights at the introduction of Basel II can be interpreted as a quasi-natural experiment. Lenders adopting IRB are the treatment group, and lenders using SA the control group. The introduction of Basel II was driven by the regulator, and was effectively a large positive supply shock, so reverse causation from prices to risk weights, via demand-side effects, is not a serious concern. IRB permissions were costly to obtain and maintain[17], and the choice was irreversible. As a result, selection into the IRB group is primarily a matter of size rather than riskiness of the balance sheet (Competition and Markets Authority, 2015).[18]

The specialisation mechanism, in the presence of the above risk weight variation, would lead banks and building societies that adopt IRB models to specialise in low-LTV mortgages, where their advantage against other lenders is larger in terms of risk weights. More specifically, IRB lenders would i) reduce their prices relative to SA lenders by more (or raise their prices by less) for low- than for high-LTV mortgages; ii) increase the share of low-LTV mortgages in their portfolio more (or decrease it less) than SA lenders. While our identification does not depend on the exact mechanism by which variation in risk weights causes price variation, one plausible story is as follows. Lower risk weights translate to lower capital requirements, which translate to lower capital resources. A lender's target return on equity (or capital, the largest components of which is equity) can be achieved with lower margins and thus lower prices, if capital resources are lower. Under competitive pressure lenders therefore pass through at least some of their comparative advantage by reducing prices.

Consistent with this prediction, mortgage prices exhibited a similar pattern of variation to risk weights. Interest rates increased temporarily after the regime change, but then dropped significantly following the decrease in the central bank policy rate, and thus benchmark lender funding rates, towards the end of 2008. Within the overall decrease, IRB lenders reduced prices by more on average, but mainly and more so at lower LTV ratios. This pattern is even clearer in Figure 3, which shows the difference between average rates for IRB and SA lenders.

[Place Figure 3 about here]

To control for confounders that could also drive co-movement between risk weights and prices, we use a differences-in-differences approach. A double difference in prices (after versus before the regime change, and IRB versus SA group) should pick up the effect of risk weights on prices. But it might also pick up effects of the financial crisis that followed close on the heels of the regime change. Fortunately, many of the effects of the financial crisis are likely to be the same across different LTV ratios, in which case adding a third difference (low versus high LTV ratio), removes them. This triple difference estimates the latent average treatment effect of using IRB versus SA, *ceteris paribus*, on how much more a lender decreases prices at low versus high LTV ratios following the regime change from Basel I to II. Assuming that the effect of IRB versus SA is mediated largely

[17]Lenders need to satisfy the regulator that they have sufficient data, modelling experience and governance controls to estimate their credit risk accurately.

[18]Of the lenders in our sample, the six largest all adopted the IRB approach, as well as four of their largest challengers (based on asset size at the time of adoption: 31 Dec 2007).

through capital requirements, conditional on our controls, the triple difference estimates can be further interpreted as implicitly capturing the causal effect of risk weights on prices.

The triple difference estimator is implemented using a regression with price (initial interest rate) as the dependent variable. We augment the regression with loan-level controls for possible variation in average risk between our comparison groups due to group composition differences. We run a similar regression for lenders' portfolio shares, as we expect that differences in prices will be reflected in quantities. We perform numerous robustness checks for alternative assumptions and find that the estimates are quantitatively robust. We test other possible causal interpretations of the triple difference estimates in three ways: additional controls; testing that the triple difference removes risk that we do not observe by studying ex-post arrears rates; and horse-racing competitor channels. None of the alternative stories we consider can explain our results. This builds confidence that we are identifying the causal effect of risk weights.

Our second approach focuses on 2009-2015, the post-Basel II period. We do not rely on a single event (the switch to Basel II), which coincided with the global financial crisis, thus providing a better estimate of the long-term effects of methodology-driven differences in risk weights on mortgage rates. We exploit the smaller methodology-driven variations in risk weights between lenders, including between IRB lenders who use different models, between LTV ratios and over time. If methodology-driven heterogeneity in risk weights leads to specialisation, then it should also be observed in variation in prices within this subsample.[19] This second approach uses much more granular variation in risk weights than the triple difference approach, which only considered average variation between two periods, two groups of lenders, and high vs low LTV ratios. We use a regression specification with price as the dependent variable, and risk weight as the explanatory variable of interest. Pairwise-interacted fixed effects for lender, time (quarter), and LTV ratios control for most alternative drivers of price, and many other confounders are controlled by including the same loan-level controls for product type and borrower risk as in the triple difference regression above.

A regression on risk weights alone does not take into account the significant variation in capital ratio requirements between lenders (Bridges, Gregory, Nielsen, Pezzini, Radia, and Spaltro, 2014; Francis and Osborne, 2009). To account for such variation we run similar regressions with capital requirements as an explanatory variable, calculated by multiplying risk weights by lender-wide capital ratio requirements. Finally, we explore potential heterogeneity in the effect of risk weights on prices, using separate sample splits for IRB versus SA, high versus low LTV, and high versus low capital buffers.

A number of implications – for financial stability, macroprudential policy, and competition policy – flow from our finding that the specialisation mechanism operates in the mortgage market.

First, from a financial stability perspective, the specialisation mechanism causes concentration of mortgage risk in lenders who have not secured permissions to use internal models for regulatory

[19]Berg, Brinkmann, and Koziol (2016) find that banks assigning a lower probability of default are more likely to provide new funding to German corporate borrowers. This is also consistent with a specialisation mechanism across IRB banks, as probabilities of default feed into risk weights in the IRB approach.

capital requirements. Such lenders are likely to have less sophisticated risk management practices, but also to be less systemically important. Concentration of higher risk (higher LTV) mortgages in smaller lenders with less sophisticated risk management may increase the expected average failure rate among the overall population of lenders, but decrease the probability of failure among systemically important lenders. Whether this is judged to be net beneficial for financial stability depends on the relative value attached to these opposing outcomes. Policy reforms that reduce the comparative advantage of IRB for low LTV mortgages could mitigate the concentration of high LTV mortgages in smaller lenders, but lead to large systemic lenders taking on riskier exposures.

Second, macroprudential tools may affect the *strength* of the specialisation mechanism. Capital buffers for systemic risk (eg on global systemically important banks) are selectively applied to lenders who also tend to use IRB. The absolute increase in capital requirements will be larger for assets which already have higher risk weights. In the mortgage market, this will reduce the IRB-SA gap in capital requirements by more at high versus low LTV ratio, and so strengthen the specialisation mechanism. Other policies that affect capital requirements heterogeneously across lenders, including Pillar 2 add-ons and the leverage ratio, could similarly affect the strength of the specialisation mechanism. Furthermore, the procyclicality of internal models versus the acyclicality of the standardised approach, means that the strength of the specialisation mechanism is procyclical (Behn et al., 2016).

Third, competition authorities have identified the IRB as a potential barrier to entry and expansion in the residential mortgage market (Competition and Markets Authority, 2015; Financial System Inquiry, 2014). The barrier would arise from the combination of high cost of IRB adoption, and the comparative advantage induced by the methodology-driven heterogeneity in risk weights between IRB and SA lenders. Our evidence confirms that IRB is indeed affecting competition in the mortgage market through the specialisation mechanism.

Finally, the specialisation mechanism, as originally theorised, is not specific to the mortgage market. Evidence for the operation of the specialisation mechanism in the mortgage market then should raise prior expectations that it also operates in other markets. In a recent contribution, Paravisini, Rappoport, and Schnabl (2015) showed, using data on loans to exporting firms, that comparative advantage leads to specialisation in bank lending.

The rest of the paper is organized as follows. Section I describes the setting and the data. Section II explains the identification strategy, and section III presents our results and robustness checks. Section IV concludes.

I. Setting and data

A. Background

Under the Basel Accords (as implemented in the EU under the Capital Requirement Regulations) banks have to meet capital adequacy requirements, which are expressed as a percentage of risk-weighted assets (RWAs).[20] Banks are required to hold capital resources of at least 8% of RWAs. Risk-weighted assets are derived by multiplying the value of each asset on the bank's balance sheet by a percentage weight (i.e. a risk weight) that reflects the riskiness of the asset. High risk assets are assigned higher risk weights; this can reflect credit risk, market risk, or operational risk. Typically, credit risk – the risk of losses arising from a borrower or counterparty failing to meet its obligations to pay as they fall due – represents by far the largest component in lenders' RWAs.

The approach to measuring credit risk has evolved over time. In 1988, the Basel I accord established minimum levels of capital for internationally active banks, incorporating off-balance-sheet exposures and a risk-weighting system which aimed (in part) not to deter banks from holding low risk assets. However, since risk weights varied only by asset class – for example, all residential mortgages had a risk weight of 50% (Basel Committee on Banking Regulation and Supervisory Practices , 1988) – the Basel Committee on Banking Supervision came to the conclusion that degrees of credit risk exposure were not sufficiently calibrated as to adequately differentiate between borrowers' differing default risks. This in turn raised concerns about regulatory arbitrage through, for example, a shift in banks' portfolio concentrations to lower quality assets (Basel Committee on Banking Supervision, 1999).

Accordingly, in 2004 the Basel Committee on Banking Supervision agreed a new capital adequacy framework, Basel II, aimed at increasing risk sensitivity by allowing banks to use internal risk-based (IRB) models to calculate capital requirements, subject to explicit supervisory approval. Those lenders lacking the financial resources and data needed to obtain approval for IRB models had to instead adopt a standardised approach (SA), in which risk weights are set in a homogenous manner across banks. Risk weights under the SA were set at the international level by the Basel Committee. For claims secured by residential property, the risk weight was reduced from a flat 50% to a range roughly between 35% and 45% based on the LTV ratio of the loan (Basel Committee on Banking Supervision, 2004).

Under Basel II, national supervisors are required to assess those risks either not adequately covered (or not covered at all) under Pillar 1, as well as seeking to ensure that lenders can continue to meet their minimum capital requirements throughout a stress event. Under this supervisory review of capital adequacy (labelled 'Pillar 2'), national supervisors must impose additional minimum requirements to capture any uncovered risks, as well as setting capital buffers which may be drawn down by distressed banks.

In the aftermath of the global financial crisis, regulators not only increased Pillar 1 minimum requirements, as outlined above under Basel III (Bank for International Settlements, 2010),[21] but also introduced a capital conservation buffer above the regulatory minimum requirement calibrated

[20] Under the most recent agreement, Basel III, these requirements reflect a minimum of 6% Tier 1 capital (made up of a minimum of 4.5% Common Equity Tier 1 capital and 1.5% Additional Tier 1 capital) and 2% Tier 2 capital.

[21] The quality standards setting out what types of capital instruments are acceptable were also increased.

at 2.5% of RWAs. [22] Moreover, a non-risk-based leverage ratio of at least 3% of Tier 1 capital was introduced, in order to serve as a backstop to the risk-based capital adequacy framework. The calibration of the leverage ratio entails that this becomes the binding constraint where the average risk weight across the bank is below approximately 35%.[23]

B. Data and summary statistics

We combine a number of data sources, starting with the Financial Conduct Authority's Product Sales Database (PSD). This dataset contains the entire population of owner-occupied mortgage sales in the UK (i.e. flow data collected at point of sale).[24] Beginning in April 2005, regulated lenders have had to submit data on all mortgage originations, including detailed information on loan, borrower and property characteristics.

These loan-level data capture the main characteristics that define a product in the UK mortgage market. The LTV ratio acts as a proxy for credit risk, but we augment this by including a range of controls to better account for risk factors that may affect pricing.[25]

We complement the PSD data with lender-level data from two other sources. First, we collected a unique set of survey data covering detailed information on lenders' risk weights. For lenders using IRB models, we use information provided by lenders in January 2016 to the Competition and Markets Authority (CMA) and the Prudential Regulatory Authority (PRA) on historical risk weights. The risk weight data are provided on an annual, point-in-time basis for the period 2008-2015, and stratified by LTV ratios. We received risk weight data for 14 out of 17 legal entities that adopted IRB models in our sample period.[26]. For lenders using the standardised approach, and for all lenders under Basel I (pre-2008), we calculate the risk weights based on the regulatory regime. [27] Second, we draw on historical regulatory data held by the Bank of England, including lender type, IRB status, and regulatory capital ratios (for both resources and requirements).[28]

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[22]A countercyclical buffer within a range of 0% - 2.5% of common equity or other fully loss absorbing capital was also introduced. The purpose of the countercyclical buffer is to achieve the broader macroprudential goal of protecting the banking sector from periods of excess aggregate credit growth.

[23]It was also agreed that large banks deemed to be systemically important would have to hold loss absorbing capacity beyond these new standards.

[24]It includes regulated mortgage contracts only, and therefore exclude other regulated home finance products such as home purchase plans and home reversions, and unregulated products such as second charge lending and buy-to-let mortgages.

[25]We include borrower type (eg first-time buyer, remortgagor), age, income, loan value, loan-to-income ratio (LTI), maturity, product type (eg fixed, floating), property value, whether or not a borrower has an impaired credit history, whether the income of the borrowers has been verified, and whether the application is based on individual or joint income. We also add information on the location of the property using three-digit postal codes.

[26]Two additional small legal entities received IRB approval but were acquired by a larger group before 2008

[27]The Basel I risk-weight was 50% on all mortgages. Under Basel II, SA lenders have a 35% risk weight for mortgages below 80% LTV ratio; for mortgages above an 80% LTV ratio, a 75% risk weight applies to the proportion above 80%. For example, a mortgage with a 90% LTV ratio carries an SA risk weight calculated as $80\%*35\%+10\%*75\% = 35.5\%$

[28]Regulatory data is as described in De Ramon et al. (2016). IRB status is based on regulatory documents giving approval for the use of IRB models. Lender-level capital ratios are expressed as percentages: the capital requirement (resource) ratio is given by total capital requirements (resources) divided by total risk-weighted assets (RWAs). Total capital requirements include both minimum requirements under Basel II (Pillar I, or 8% of RWAs) as well as lender-specific supervisory add-ons (Pillar II). Total capital resources include all classes of regulatory capital, including Common Equity Tier 1, Additional Tier 1, and Tier 2.

When matching the lender-level risk weight and capital ratio data (submitted annually and quarterly, respectively) to the loan-level data in PSD, we assigned each loan to the closest available data point by date. The implicit assumption underlying this matching is that, when lenders price new lending and allocate capital across business lines, they consider the risk weights and capital ratios that apply at the time their capital requirements are set. That is, lenders use risk weights and ratios that apply to their current book to forecast the capital requirements they will incur in the future on the mortgages that they are currently originating. This is likely to be a reasonable approximation; it is also a practical one, as it would have been difficult to obtain estimates of risk weights at origination.

Our dataset was subject to several cleaning steps. Lenders who were not banks or building societies were excluded,[29] as were niche or uncommon products or borrowers (such as lifetime mortgages or council tenants buying social housing). Loans with missing data on key variables (eg on interest rates, or on IRB risk weights in the case of our second model) were dropped. We identified a small proportion of observations in our dataset as referring to the same loan – these were aggregated. Finally, some lenders were excluded from our analyses for idiosyncratic reasons. These reasons include mergers and acquisitions activity (common in the crisis and post-crisis periods), partial use of IRB models, or known data quality issues.[30] Finally, key variables were winsorised based on pre-defined outlying values, removing no more than 1% of the distribution in each case. The total effect of our cleaning steps was to reduce the size of our sample from approximately 14 million observations to 7 million. The largest part of this reduction was due to missing data (especially on interest rates or risk weights) and excluding lenders who were not banks or building societies).

For much of our sample period, we observe interest rates on mortgages, but not up-front product fees. This has two implications. First, fees can be included in the loan value we observe (and therefore in the LTV ratio), but fees are not included in a lender's calculation of LTV ratio when determining pricing thresholds. In light of this, we made a threshold adjustment to the LTV ratios in our sample based on the subset observations for which we do observe product fees.[31] Second, this means we observe only one component of price. If SA lenders had systematically lower fees than IRB lenders, then a differential in interest rates could exist without reflecting a meaningful difference in price. In practice, based on available data we do not observe a systematic difference between IRB and SA lenders in terms of pricing structure.

Table I summarises the key variables used in our analysis. We report four sets of summary statistics: column (1) reflects the total population of loans by banks and building societies over our

[29]These two categories account for 90% of the UK market over our sample period. Besides banks and building societies, the other major segment of the UK mortgage market are specialist lenders, who we hope to include in future analysis.

[30]Notable lenders dropped include Northern Rock, The Mortgage Works and UCB. Observations from Lloyd's Banking Group and TSB were excluded in the early part of the sample, because merger activity and the spin-off of TSB in 2013 meant that we were not able to obtain consistently-calculated risk weights over the whole sample.

[31]Loans that are very close (within 0.5-1%) to the bottom of an LTV band are included in the lower band. For example, we place a loan with an LTV of 75.5% in the 70-75% LTV band.

sample period; (2) the subsample used to estimate the triple-difference (DDD) model; (3) shows a date restriction on the full sample (2009 through 2015); and (4) represents the sample used in the RW model, which is subject to the same date restriction as (3) as well as all additional exclusions and cleaning. The intention is to compare (1) with (2), and (3) with (4), in each case to show any effect of the cleaning steps outlined above. The bulk of the reduction in observations is due to missing data, notably on interest rates and risk weights, which are critical for our analyses.[32] The exception to this is our calculation of portfolio shares, which requires no information on rates or risk weights, so column (1) is used for this purpose.

From a comparison of column (1) and (2) we see that characteristics of key variables do not appear to be materially different, suggesting one should not be concerned about selection bias. A similar conclusion can be drawn when comparing columns (3) and (4). Even in our most selective sample we observe close to four million loans.

Panel A of Table I reports loan-level variables. The 'average' mortgage in the full sample has an interest rate of 4.2%, a loan value of roughly £140k, an LTV ratio of 63%, and a maturity of 22 years. Fixed-rate mortgages account for approximately 70% of loans in the sample, although they are not fixed for long: the duration of the initial period is usually short in the UK mortgage market. The average risk weight on mortgages (across all LTV ratios and lenders) is 29% for 2005-2015 and 13% for 2009-2015. This low risk weight is driven by the large share (90%) of mortgages issued by IRB lenders.

In Panel B we display the key borrower characteristics we use in our analysis. The average borrower (again, in the full sample) is 39 years old, has an income of slightly more than £50k and is taking out a mortgage on a property worth £240k. The average loan-to-income (LTI) ratio is close to 2.8. Our data is almost exclusively made up of prime mortgages: the fraction of subprime borrowers (those with impaired credit histories) is less than 1%. The income is verified in 67% of the transactions, and 51% are joint mortgages, i.e. those with two incomes. The fraction of first-time-buyers (FTB) is about 21%, while remortgagers account for approximately 43% of loans. In our sample we have 93 banks and building societies (legal entities), of which 19 use IRB models for at least part of the sample period.

II. Identification strategy

This section explains how we identify the causal effect of methodology-driven variation in risk weights on prices and quantities, and test the hypothesis of specialisation by LTV ratio under Basel II. We expect risk weights to have a positive causal effect on prices. Higher risk weights imply higher capital requirements – the primary component of which is equity – so to achieve the

[32] During part of our sample period, reporting loan-level interest rates in the Product Sales Database was optional. A few lenders chose not to do so, and we drop these observations for the relevant period when performing analysis on prices. In addition, some smaller IRB lenders were not included in the historical risk weight survey, so these lenders are not included in the sample for the risk weight pass-through model.

same return on equity (RoE) a lender must increase their interest rates.[33] To the extent they do this, rather than accept a lower RoE, prices will rise.

Risk weights and prices are strongly correlated (the Pearson correlation coefficient is around 0.6), and graphical analysis discussed in the introduction (see Figures 1, 2 and 3) shows strikingly similar patterns of variation in prices and risk weights.

But risk weights might be correlated with other factors affecting pricing. The hardest factors to control for are those related to risk, because after all risk weights are intended to reflect risk (plus a margin of conservatism in the case of SA). Risk is priced by setting an interest rate equal to expected credit loss (ECL) plus a margin to compensate for the economic capital held by risk-averse banks against unexpected loss.[34] Other important costs that could affect pricing include funding and operational costs, which tend to vary at bank-level,[35] and interest rate swap costs for fixed rates and repayment timing options embedded in particular products. The former can be correlated with risk weights if lenders with lower operational costs invest in better internal model; the latter can be correlated with risk weights if products with longer fixed rates are on average riskier.

To identify the causal effect of risk weight variation on mortgage prices, we use two complementary and related strategies. Each exploits a different part of the total methodology-driven variation in risk weights. In section II.A, the first approach exploits the regime change from Basel I to II – which induces quasi-natural experimental time variation in risk weights between both lenders and LTV ratios – using a regression triple-difference (DDD) estimator. We start with a simple specification then augment this with various controls as robustness checks. We look at both prices and quantities.

The second approach in section II.B exploits methodology- (as opposed to risk-) driven variation in risk weights within the Basel II regime, using a regression specification with pairwise interacted fixed effects. Controls are similar to the DDD approach. Risk weights appear directly in this regression (rather than implicitly in an IRB group dummy) so we can capture the more nuanced variation within the Basel II regime.

Both approaches base identification on the fact that risk weights vary within banks by LTV ratio, as well as between banks and over time. We can thus completely control for everything that varies at bank level but is fixed within bank, and still identify our effect.

A. *Triple difference model (2005-15)*

Our triple difference (DDD) specification exploits methodology-driven risk weight variation arising from the regime change from Basel I to II at the start of 2008. We interpret this as a quasi-natural experiment, with IRB and SA lenders as the treatment and control groups respectively.

[33] A binding leverage ratio requirement could make the lender insensitive to risk weights. This is not important in our sample because the UK leverage ratio requirement was only introduced in 2013, and was only binding for a couple of lenders. Our results are robust to excluding these lender-years.

[34] UK mortgages are priced on a menu basis, rather than negotiated, so borrower-level heterogeneity in risk is not priced directly, but in anticipation of attracting and accepting a target risk profile.

[35] Or at the level of the mortgage business unit within the bank.

The change in regulations induced risk-weight variation in three dimensions as illustrated in Figure 2: lender (those choosing IRB versus SA), time (after versus before the regime change), and LTV ratio.

There were distinct movements in each of these three dimensions. First, a sudden and large fall in risk weights across all lenders (upper panel). Second, the average fall among IRB banks was larger than the average fall among SA banks. Third, the gap that this opened up was considerably larger at low versus high LTV ratio (lower panel). For identification we exploit this last component of the variation: that risk weights fell more within the IRB group than within the SA group, and this gap was larger at lower LTV ratio.

The risk weight variation induced by the regime switch can be interpreted as a large positive supply shock, so in estimating the effect on prices we need not worry about reverse causality from prices to risk weights. Selection into the IRB group was the result of a bank's choice (subject to regulatory approval) rather than random assignment, so we must consider the potential for selection bias. The primary benefit of adopting IRB derives from the reduction in risk weights, and scales with balance sheet size. The costs are largely fixed and non-recoverable (voluntary reversion to SA is not permitted) so net benefits depend on economies of scale (Competition and Markets Authority (2015), consistent with supervisory experience). As already explained in I.B, all the largest lenders adopted IRB, while the smaller ones, with very few exceptions, adopted SA.[36] Treatment and control groups therefore differ in factors correlated with size that are relevant for mortgage pricing, such as unit funding and operational costs, expected credit loss (ECL), and margin targets.

A difference-in-difference estimate (pre versus post the regime change, and IRB versus SA groups) would control for time-invariant differences between the IRB and SA group (eg size) and for factors that exhibit parallel time trends between the IRB and SA groups (eg macro-financial factors common to all lenders). But the near-contemporaneous global financial crisis could have caused deviations from parallel trends in priced factors including ECL, funding costs and capital buffers.[37] First, ECL generally increased post-crisis, and more so at higher LTV ratios. IRB and SA groups had different portfolio shares in high LTV ratio before the regime change, so would have had non-parallel trends in average ECL. Second, larger lenders had lower buffers going into the crisis, greater reliance on securitisation markets and greater exposure to US subprime mortgages. These factors could have led to an increase in funding cost for larger lenders relative to smaller ones.

To control for such deviations from parallel trends we use a triple difference identification strategy which removes any confounders that vary along one or two but not all three dimensions. Identification is thus based on joint variation along all three dimensions. Our regression implementation is:

[36] In a certain size range the choice may be finely balanced, inducing selection on risk and causing us to overestimate our effect. But the discontinuity in the size distribution probably means few banks are in this range, our controls for risk mitigate any selection bias, and robustness checks below suggest none remains.

[37] Unless stated otherwise, capital buffers, or simply buffers, refers to the voluntary surplus of capital resources over all requirements including regulatory requirements that are labelled as buffers.

$$Interest_{ilbt} = \beta_1 BaselII_t + \beta_2 IRB_l + \beta_3 LowLTV_b + \beta_{12} BaselII_t \times IRB_l + \beta_{13} BaselII_t \times LowLTV_b + \beta_{23} IRB_l \times LowLTV_b + \beta_{123} BaselII_t \times IRB_l \times LowLTV_b + \alpha Controls_{ilbt} + \epsilon_{ilbt} \quad (1)$$

$Interest_{ilbt}$ is the initial interest rate charged to borrower i by lender l for a mortgage in LTV band b originated in period t. $BaselII_t$, IRB_l, and $LowLTV_b$ are indicator dummies for loans originated respectively after the regime change, by lenders that choose IRB at any time during the sample period,[38] and at or below a specified LTV ratio threshold (75% in our baseline). $Controls_{ilbt}$ is a vector of loan-level variables which control for relative risk and other priced factors as discussed below.

Some confounders might exhibit residual variation even after triple differencing. Unless further controls are applied, this could bias the estimation of β_{123}.

Risk is likely to exhibit residual variation, since it is correlated with risk weights by design. For example, larger banks tended to securitise more of the mortgages they originate and thus have had less incentive to screen loan quality pre- versus post-crisis when more loans stayed on its book. This externality could have been more marked at higher LTV ratio where soft information could be more important (Keys, Mukherjee, Seru, and Vig, 2010; Purnanandam, 2011; Keys, Seru, and Vig, 2012).

Residual risk variation is controlled for in our baseline specification by additional borrower and product characteristics.[39] Both segment the market and help to control for variation in the competitive environment, pricing strategies and risk. For example, fixed rate mortgages entail swap costs, but variable rate mortgages do not.[40]. Cash flow timing options (eg prepayment, payment holidays, offsets against savings) involve hedging costs for expected behaviour and economic capital to cover unexpected behaviour.

Differences in lenders geographical focus could also give risk to residual risk variation, because of differences in local economic shocks. We therefore check robustness to the inclusion of postcode fixed effects. This also tests robustness to residual variation in competition and pricing strategy arising from residual geographic exposure variation.

To complete our battery of robustness checks against residual risk variation, we include a full set of pairwise interacted fixed effects between lender, LTV ratio and quarter dummies. The LTV-time and LTV-lender fixed effects control more aggressively for the variation of risk by LTV ratio, which is only approximately controlled by the binary LTV high versus low bands used in the

[38] One lender in our sample, accounting for a small fraction of loans made after the regime switch, was granted IRB permissions at a later date than the regime change.

[39] Borrower characteristics are: loan-to-income (LTI) ratio, a dummy for joint income applications, a dummy for impaired borrowers and dummies for the type of borrower (First-time buyers vs. home movers vs. re-mortgagors). Product characteristics are: rate type (fixed vs. variable) and repayment type (capital and interest vs. interest only).

[40] Swap costs could become correlated to risk and thus to IRB risk weights via selection of riskier borrowers into products with shorter fix periods, and poorer performance among such borrowers when interest rate risk moves against them.

baseline specification. For example, the lender-time fixed effects control for funding costs more comprehensively than the triple difference alone.

Robustness to key modelling assumptions is checked as follows. The threshold between high and low LTV ratio is essentially arbitrary. We use a threshold of 75% in our baseline results, but check robustness to a 5pp variation in either direction. Since the financial crisis was arguably an exceptional period, we also check robustness to excluding crisis years from our pre and post periods. We also check robustness to sample selection in the lender dimension. We exclude 'late switchers' to IRB for two reasons. First, this tests our assertion that there is not substantial bias from selection on risk. The excluded lenders are the most natural candidates for selection bias, because they are mid-sized and hesitated to switch. Second, this checks that results are not sensitive to the measurement error we induce by categorising late switchers as IRB lenders for the entire Basel II period. To check robustness to time variation in composition of the IRB and SA groups, we also estimate the coefficient on a balanced subsample of our data.

This leaves a couple of alternative causal explanations that we cannot control for. But we can test for evidence of them indirectly.

Unobserved residual risk variation cannot be controlled directly. But we do observe the ex-post realisation of that risk in the form of arrears rates, on a subsample of loans, which we can interpret as a proxy for ex-ante risk.[41] We test the null hypothesis of zero residual variation in this risk proxy by replacing the dependent variable in the above regressions (the interest rate) with a dummy for whether the loan is in arrears at a snapshot date, which gives a linear probability model for arrears, and testing whether the coefficient on the triple interaction term is significantly different from zero.

Differential exposure to the global financial crisis could also provide an alternative explanation of our results. The impact of the crisis may have been bigger for larger lenders due to their greater exposure to risk shocks outside the UK mortgage market, such as US subprime losses. This could have led to increased risk aversion among larger banks (a "differential flight to quality").

To test if this channel could explain our results, we proxy for lenders' exposure to shocks related to the financial crisis in two ways: ex-ante through pre-crisis capital buffers; ex-post through increase in funding costs. First, we horserace high exposure due to low capital buffers against the risk weight channel. We do this by augmenting our baseline regression with an additional triple interaction term in which the IRB dummy is replaced with a low capital buffer dummy. That dummy indicates lenders whose mean buffer in the pre-crisis period was below the median. Second, we test high exposure as proxied by increases in funding costs. We only have this information for lenders in the IRB group, so we cannot implement a horserace.[42] Instead, we test whether IRB lenders who experienced a larger increase in funding costs after the regime switch exhibit a larger

[41] Arrears are the ex-post analogue of probability of default. With hindsight, ex-ante risk measures were likely biased downwards before the crisis, leading to an offset between observed ex-post measures and unobserved ex-ante risk. But since our test depends on residual variation, any bias which is fixed across either LTV ratios or IRB and SA lenders is removed by triple differencing. Moreover, sample selection is driven by incomplete coverage of the data collection exercise, which is not obviously correlated with risk.

[42] Harimohan, McLeay, and Young (2016) use the same data to study the pass-through of funding cost into mortgage and deposits rates.

relative reduction in prices for low versus high LTV ratio mortgages. We implement this using a version of our baseline specification in which, instead of the triple interaction term involving the IRB dummy, we include a dummy indicating lenders whose funding costs increased by more than the median increase.

To further study if the difference in risk weights affected lenders' specialization we look at lenders' portfolio shares. We estimate the following triple difference specification:

$$\begin{aligned} Share_{lbt} = & \beta_1 BaselII_t + \beta_2 IRB_l + \beta_3 LowLTV_b + \beta_{12} BaselII_t \times IRB_l + \beta_{13} BaselII_t \times LowLTV_b + \\ & \beta_{23} IRB_l \times LowLTV_b + \beta_{123} BaselII_t \times IRB_l \times LowLTV_b + \epsilon_{lbt} \end{aligned} \quad (2)$$

Where $Share_{lbt}$ is the shares of mortgages for each lender in each LTV band in each quarter. As in model 1 our coefficient of interest is the one on the triple interaction (β_{123}) that we now use to measures the effect of risk weights on portfolio shares. It indicates if banks adopting IRB models increase their portfolio shares by more for low LTV ratio mortgages, as a results of their comparative cost advantage in that segment.

B. Post-Basel II risk weights model (2009-15)

In this section we develop our second identification strategy, which focuses on the marginal effect on prices of methodology-driven differences in risk weights under Basel II. By focussing on the post-Basel II period only we lose the quasi-experimental variation in risk weights resulting from the switch from Basel I to II, and the variations in risk weights under Basel II tend to be relatively smaller in scale. However, we can exploit the unique dataset that we collected on risk weights at the lender-LTV ratio level for the period 2009-2015. Thanks to this data we can capture differences in risk weights not only *between* IRB and SA lenders, but also *within* the set of IRB lenders (already shown in Fig 1). Given that the majority of new mortgages are issued by IRB lenders, a within IRB comparison will reveal potentially important effects of risk weights on mortgage pricing that we cannot identify with the IRB dummy used in the triple difference model.

Moreover, we can measure the intensity of treatment due to the adoption of IRB models, without being constrained to a binary treatment indicator. In this way we can inform policy about what happen if there is a percentage increase in risk weights and not only a switch from SA to IRB. The results can be seen as a simplified "pass-through" effect of regulatory risk weights into mortgage rates.[43] In addition, we do not rely on a single event (the introduction of IRB models), which coincide with the global financial crisis and the subsequent policy responses, thus providing a better estimate of the "equilibrium pass-through" of methodology-driven differences in risk weights

[43] A full pass-through model requires the knowledge of the marginal cost of issuing a mortgage. To do that, we need information not only about the cost of capital and the capital requirement, but also about the funding mix of the lenders. We also add information of the minimum capital ratio that lenders have to hold to calculate LTV-specific capital requirements. We do not have information on heterogeneity in the cost of capital and cost of debt to estimate a full pass-through model

to mortgage rates.

Our identification approach seeks to isolate the effect of methodology-driven variation in risk weights. This includes the variation between average IRB and SA risk weights, since the SA risk weights are given by the regulator. This variation is modest because the SA risk weights only vary with LTV ratios above 80%. But crucially, we want to isolate methodology-driven variation between IRB lenders, due to use of model differences that would cause different risk weights even on identical underlying risk, and similarly within IRB lenders due to model variation over time.

The cost of changing IRB models is arguably lower than the cost of switching from IRB to SA, and IRB lenders have incentives to implement changes in their models only if they reduce risk weights. This could lead to endogeneity due to selection. Methodology-driven variation would be limited if lenders could cherry-pick the best model for each LTV ratio level (or more in general for each risk/loan) without constraints. We can limit our concerns about selection driving risk weights for at least three reasons. First, revisions in lenders' models need to be approved by the regulator, and these revisions should reflect improvements in the models' ability to capture risks (in some cases, revisions are initiated by the regulator to address weaknesses in the model). Second, in our specification average changes in the model at the bank level are controlled through fixed effects (bank-time dummies, see below). Third lenders' models by construction are based on historical data on PDs and LGDs so that we can rule out reverse causality to risk weights. In addition, a recent study by the Basel Committee on Banking Supervision (2016a) finds considerable variability in risk weights for residential mortgages due to internal models.

As with the triple difference model, we need to control for other confounders that affect pricing, in particular risk. Variation in risk weights between IRB lenders and within IRB lenders will likely reflect genuine differences in risk (other than LTV ratios, which we will control for using LTV band dummies), and for clean identification we need to disentangle these from variation in risk weights that is driven by regulation (SA vs IRB) or model differences (within IRB) on which we base identification. To control for other confounders, we estimate to a specification with pairwise interacted fixed effects, and the same product- and borrower-specific controls used in triple difference model). However, our coefficient of interest is no longer a dummy, but lender-time-LTV specific risk weights.

We estimate the following model:

$$Interest_{ilbt} = \gamma_{lt} + \gamma_{lb} + \gamma_{bt} + \beta RW_{lbt} + \alpha Controls_{ilbt} + \varepsilon_{ilbt} \quad (3)$$

The dependent variable is the same as in model 1. Our coefficient of interest is β, which measures the effect of risk weights on mortgage rates. To isolate the effect of risk weights we include interacted fixed effects for lender-time (γ_{lt}), lender-LTV (γ_{lb}), and LTV-time (γ_{bt}). In this way we control for all time-varying unobservables across lender and LTV ratios and for time-invariant differences at the bank-LTV level. As a result, we can rule out alternative drivers of interest rate differentials, along the lines of the triple difference model (equation 1), but with more granular dummies.

Lender-time fixed effects control for change in funding and operational costs, and for anything else that is fixed within a lender-time pair. Lender-LTV band dummies control for time-invariant (or time-averaged) components of the bank's relative pricing across LTV ratios, such as business model / pricing strategy / market positioning and risk appetite/aversion. LTV band-time dummies control for much of the industry-wide variation in the external environment (competition and risk).

Even after controlling for unobservable time-varying lenders and LTV ratio segments effects with dummies, our coefficient β may be biased if (i) lenders price in credit risk which is unobservable to us, and (ii) this unobserved credit risk is correlated with risk weights. We reduce this risk by adding loan-level controls for credit risk (as in model 1).

Because risk weights are a function of risk, these controls also remove variation in risk weights. For example, borrower-specific controls capture variation in probabilities of default (PD). But PDs feed into risk weights models, and will also remove some variation in risk weights. Lender-time fixed effects will remove the effect of methodology to the extent that it affects risk weights for a specific lender across all LTV ratios. Lender-LTV fixed effects remove the time-invariant effects of methodology on specific LTV ratios. LTV-time fixed effects remove shocks to methodology that are common across lenders (eg changes in regulatory approach).

Our fixed effects vary only along two dimensions, and we retain variation along the combination of all three dimensions. After adding loan-level controls we only retain risk weight variation that is: a) idiosyncratic to specific combinations of LTV ratio, time and lender, b) uncorrelated with borrower-specific risk characteristics (as far as these are observed through our controls). As shown in Figure 1 for 2015, we focus on heterogeneity across lenders within an LTV-time period.

Lenders with higher capital ratios should benefit more from methodologies that yield lower risk weights, thus any advantage in risk weights is magnified by higher capital ratios. As described in section I.B, we have information on lender-level minimum capital ratios calculated as Tier 1 capital divided by risk-weighted assets.[44] In the UK, capital requirements vary across time and lenders.[45] We calculate LTV-level capital requirements as the product of LTV-lender-time risk weights and the lender-time capital ratio. To test whether the interaction with capital ratios is reflected in prices, we estimate the following model:

$$Interest_{ilbt} = \gamma_{lt} + \gamma_{bl} + \gamma_{bt} + \delta_{req} RW_{lbt} \times CapReq_{lt} + \alpha Controls_{ilbt} + \varepsilon_{ilbt} \tag{4}$$

In this model, we simply substitute risk weights in model 3 with capital requirements at LTV-level.[46] Our coefficient of interest is δ_{req}, which measures the effect of LTV-level capital requirements on mortgage rates. We expect the coefficient to be positive. All other variables are as in model 3. As a robustness check, we also estimate the same model with capital resources instead of the minimum capital requirement, i.e. the available Tier 1 capital divided by risk weighted assets at

[44]For simplicity, we include all elements of the capital ratio. But it is possible that Pillar 2 and buffers, which are not directly tied to specific risk weights, are allocated in a different way from Pillar 1. Supervisory evidence suggests that some lenders do distinguish between different types of capital requirements in their pricing.

[45]The variation is mainly due to capital add-ons under Pillar 2, but also to the leverage ratio.

[46]More accurately, the capital requirements are at LTV-time-lender level, but we only refer to LTV-level to clarify that we are not referring to standard lender-wide requirements.

lender level [47].

Finally, we look at capital buffers, the difference between resources and requirements. We expect lenders with low buffers to be more sensitive, in their pricing, to methodology-driven differences in risk weights. Since raising external equity is costly, lenders with low buffers are more constrained in their ability to lend. Lenders with high buffers instead have more margin to adjust to changes in risk weights.

Despite our rich set of loan level controls, we cannot fully rule out variation in risk weights due to unobserved risk. However, for low-LTV loans, the expected loss even at a high probability of default is minimal, given that the lender can recoup their investment in the vast majority of cases. With this in mind, we wouldn't expect a material amount of residual credit-risk-based pricing in low-LTV loans, so any bias to our estimates should be minor. We run robustness checks comparing estimates for low versus high LTV ratio. If we have controlled properly for risk, the estimated coefficients for high LTV ratio should not differ to the one for low LTV ratio (which we know has no material amount of residual risk-driven variation).

III. Results

In this section we show our main results. We first exploit the change in regime from Basel I to II and we show in III.A the effect of the gap in risk weights between IRB and SA lenders on prices and portfolio shares. Then we exploit the variation under Basel II in both risk weights and capital requirements and show the marginal effect of risk weight methodology on prices in III.B.

Throughout the section we focus on the effect on pricing of methodology-driven variation in risk weights. When we present our results we sometimes omit methodology driven and refer simply to the effect of risk weights on pricing.

A. Triple difference model (2005-15)

In this section we present several results from our triple-difference identification strategy. First, we look at whether lenders adopting the IRB approach changed their mortgage pricing differently from those adopting the SA. Second, we test if this change in pricing was accompanied by a change in specialization. Last, we "horserace" our channel with alternative mechanisms that could have affected the differential pricing we find in the data.

Table II summarises our results. We report only the coefficient on the triple interaction term from model 1 and discuss in appendix C a full decomposition of the different interactions in the model. Panel A shows the impact on pricing. Column (1) shows our benchmark model from equation 1. We find that IRB lenders decrease rates, compared to SA lenders, more on low-LTV ratio mortgages relative to high-LTV ones after the introduction of Basel II. The effect is statistically significant and economically relevant: the gap in rates is about 32bp.

[47] If lenders use risk weights not only to calculate their capital requirements, but also allocate their economic capital (their capital resources), then higher level of resources will be reflected in pricing.

In the other columns of panel A of table II we test the robustness of this result to specification assumptions and the inclusion of additional controls. First we consider alternative thresholds for high and low LTV ratio mortgages. The results remain significant and the coefficient on the triple difference confirms that IRB lenders decrease average relative interest rates more on low LTV ratio mortgages. The changes in the magnitude go in the direction we expect. A lower threshold makes the effect even stronger, as we can see from column (2). This is due to the fact that at lower LTV ratios the gap in risk weights between IRB and SA is larger (see figure 1). A higher threshold goes in the opposite direction, but the results are still significant and the magnitude large (column (3)).

In columns (4) and (5) of table II we estimate the benchmark version of model 1 in two subperiods of our sample. We compare the years 2005-2006 with 2009-2010 and 2011-2012, thus excluding the year just before and after the change in regime. The coefficients on the triple interaction remain statistically significant and the magnitude increases for the years 2009-2010 and is almost unaffected for the years 2011-2012. These results confirm that we are capturing a long-term effect of risk weights on prices and not only a transitory change due to the switch from Basel I to Basel II, reflecting the fact that the gap in risk weights between IRB and SA represents a permanent feature of Basel II.

The composition of the IRB and SA groups vary in each year, due to missing data for a few IRB bank-periods, and a few cases of market entry and exit (including mergers). To verify that this does not strongly affect our results, we estimate the model on a balanced panel in column (6). By focusing on this set of lenders we can rule out effects driven by lender selection. The coefficient remains statistically significant and the magnitude is almost unaffected.

Variation in lenders' geographical pattern of origination could affect pricing through credit risk. Differential economic conditions across regions in the UK can affect pricing through probability of default (eg local unemployment shocks) and loss given default (eg local house prices fluctuations). The exposure to local shocks will differentially affect lenders depending on their market shares across the UK and will be especially relevant for less-diversified smaller lenders (eg building societies).We therefore check the robustness of our results to the inclusion of postcode fixed effects. Column (7) shows that our results remain statistically and economically significant.

Many of the confounding factors outlined in section II vary between individual banks, rather than between IRB and SA groups; and between the specific LTV bands, rather than between binary high and low LTV bands. The binary differences (or their equivalent dummy variables in a regression implementation) only provide approximate controls. In column (8) of table II we include the full set of interacted fixed effects for lenders, LTV ratios and quarter.[48] The coefficient on the triple difference remains statistically significant and the magnitude decreases by about 5bp. In this specification we are controlling for both time-varying and time-invariant idiosyncratic differences across lenders and LTV ratios, thus absorbing some of the variation coming from the regime change. We see the fact that the coefficient of interest is only slightly reduced as corroborating our main

[48]These are the fixed effects that we use in our benchmark specification for the analysis within Basel II in section III.B.

hypothesis.

In panel A of table II we show that IRB lenders after Basel II decrease interest rates on low LTV mortgages relative to SA lenders. In panel B we study if this pricing strategy had an impact on the shares of low and high LTV mortgages, leading to specialization. Studies of the impact of capital on corporate lending can exploit multiple borrowing relationships to control for risk (Khwaja and Mian, 2008). That approach is not feasible for mortgage lending, because at any point in time households typically have only one mortgage from one lender. However, we can test if the differential treatment of risk weights had an impact on originations by looking at lenders' portfolio shares.[49] The first column of panel B in table II shows that IRB lenders increase their portfolio shares with respect to SA lenders on low LTV mortgages relative to high LTV after Basel II. Again the effect is statistically significant and economically relevant: IRB lenders increase their relative share on low LTV mortgages by approximately 12% relative to SA lenders after the shift to the new regime. We perform the same robustness checks as in panel A for interest rates and the results are very similar. The triple-difference coefficient remains statistically significant and the magnitude varies in the range between 12% and 16%.

The joint behaviour of prices (rates) and quantities (portfolio shares) is consistent with the new risk-weight regime offering IRB lenders a relative advantage on low risk (low LTV) mortgages. But there may be unobserved borrower characteristics that changed differentially for IRB and SA lenders at the same time as Basel II was introduced. Eg, IRB lenders may have increased their screening of borrowers and select the safer ones within different LTV segments.[50] As a result, the relative decrease in prices by IRB lenders for low-LTV loans may have been driven by a better pool of borrowers, irrespective of the risk weights treatment. We address this concern by matching our originations data with performance data for a subsample of the loans. We then run a linear probability model in the same spirit of the triple difference model of equation 1, where the dependent variable is a dummy equal to one if the loan is in arrears in 2011. Panel C of table II reports our results. We find that low-LTV loans originated by IRB lenders after Basel II are ex-post more likely to be in arrears than low-LTV loans originated by SA lenders, suggesting that the pool of borrowers for IRB lenders was worse, not better, than the pool for SA lenders. This result is robust to different specifications and additional controls. Differential selection of borrowers between IRB and SA lenders within an LTV segment is unlikely to be driving our results.

A second threat to our identification strategy comes from omitted variables that can affect lenders' relative pricing of mortgages with different risk profiles. If IRB lenders were more exposed to the financial crisis than SA lenders they may have de-risked more across their balance sheet, including in their UK residential mortgage portfolio, where de-risking may have resulted in a relative increase in portfolio shares and a relative reduction in pricing at low LTVs. We address these concerns in table III, using additional information on lenders' capital buffers and funding costs as proxies for exposure to the financial crisis.

[49]Given that we aggregate individual loans at the lender-segment-quarter level we cannot control for individual characteristics and borrower location.

[50]Note that we are controlling for average borrower selection between IRB and SA lenders with the first difference.

In columns (1) to (3) of table III we “horserace” the IRB dummy with these alternative measures of exposure to the financial crisis. Column (1) shows again the result from our baseline specification. In column (2) we interact the dummy on low LTV mortgages after Basel II with a dummy for lenders whose capital buffer at the end of 2007 was below the median. If lenders that had lower capital buffers wanted to attract lower risk mortgages after the crisis, the differential effect will be captured by the triple interaction. We do not find any significant result. In column (3) we consider both interactions jointly and we see that the IRB dummy remains significant and the magnitude is even larger. A lower buffer per se does not explain the differential pricing of low LTV mortgages after the introduction of the new Basel II regime.

Lenders more affected by the crisis may experience a higher increase in funding cost. This is a threat to our identification strategy if differential shocks to funding costs between IRB and SA lenders led to differential pricing for high and low LTVs. We cannot fully “horserace” this alternative channel with our IRB dummy because we do not have funding cost data for SA lenders. However, we run a placebo test within the group of IRB lenders, using dummies for lenders that experienced an above-average increase in funding cost for term unsecured debt after 2008. We then interact this measure of the increase in funding cost with the dummies for post-Basel II and low LTV mortgages. The triple difference coefficient in column (4) of table III shows that lenders experiencing a larger increase in funding cost do decrease rates more for low LTV ratio mortgages, but the effect is indistinguishable from zero.

To summarize, we find that the introduction of Basel II provided IRB lenders with a more favourable risk weight treatment at low LTV mortgages and this led to repricing and specialization. As a result of the risk weight “discount” IRB lenders decreased prices by 32bp and increased their portfolio share by 12% in low risk mortgages relative to SA lenders. These effects do not seem to be driven by borrower selection, by differential exposure to the crisis, ex-ante in terms levels of capitalisation or ex-post in terms of changes in funding cost.

B. Post-Basel II risk weights model (2009-15)

In this section we show the results of model 3, which exploits the granular variation in actual risk weights within the new regime. Table IV presents the main results. All our specifications include interacted time, lender and LTV fixed effects. In this way we control for all time varying factors affecting pricing and we rely only on the differential variation in risk weights across lenders and LTV over time. In column (1) we report the coefficients of the benchmark specification. We find a significant coefficient of 0.01,.implying that a 1 percentage point differential increase in risk weights translates into a 1bp increase in the interest rate. This result can be interpreted as an estimate of the “pass-through” to prices of methodology-driven differences in risk weights. For mortgages below 50% LTV, the average difference in risk weights between IRB and SA lenders is about 30 percentage points. Given our estimate of the pass-through coefficients, such a difference will translate into a price gap of about 30bp. This gap at low LTV is in line with our results from the triple-difference model in section III.A.

In the rest of table IV we refine our pass-through model by including additional information on the time-varying lender capital requirement and resources. The specification in column (1) assumes that the capital requirement is the same across lenders. However, in the UK capital requirements vary significantly across lenders and over time (Bridges et al., 2014; Francis and Osborne, 2009). To account for this we construct loan-level capital requirements by interacting the risk-weight with the capital requirement for each lender in each quarter. We find that an increase in the loan-level capital requirement by 1% translates into a 6 basis point increase in prices.[51]

Many of the lenders in our sample have capital resources that are six percentage points or more above their requirement. Actual resources, rather than requirements, can then affect the pass-through of risk weights into mortgage rates. We test for this alternative hypothesis on the relevance of resources versus requirement in column (3) of table IV. We find that a 1% point increase in capital resources translates into a price increase of approximately 3.5bp.

Table IV presents the average pass-through of methodology-driven differences in risk weights and loan-level capital requirements into interest rates. However, the pass-through of risk weights can vary across lenders and mortgage types. In table V we look at heterogeneity according to lenders' model, capital buffer and the riskiness of the loan, as measured by the LTV ratio. In column (1) we estimate our model on the subsample of IRB lenders. The coefficient on risk weights remains significant and the magnitude is largely unaffected. In column (2) we report the coefficient for the SA only group. As expected, we do not find a significant effect of risk weights. The LTV segment dummies capture almost all the variation within the SA group, whose risk weights are set by the regulator. The residual variation comes from mortgages with leverage above 80%, but again the left variation in risk weights for SA lenders after the inclusion of the bank-segment dummies is minimal.

As a second dimension of heterogeneity we look at lenders' time-varying capital buffers. We expect lenders with higher buffers to be less sensitive to differences in risk-weight, as they have more margin to adjust relative to lenders with little or no extra capital. To test this hypothesis we compute the median capital buffer over the sample period we analyse and we divide lenders into high buffer and low buffer groups, depending on whether they are (on average) above or below the median buffer of 6%. We find that for lenders with high buffers prices do not respond to risk weights, while the pass-through is significant for low buffer lenders. Lenders with a tighter buffer increase the rates by 1.7bp for a differential 1% increase in the risk weights.

As discussed in section II.B, we check for potential bias in our estimates due to unobserved risk characteristics by comparing the coefficients on risk weights in equation 3 for high- and low-LTV loans. We don't expect a material effect of unobserved risk for low-LTV, so any bias to our estimates should be minor. A similar coefficient for high and low LTVs would then suggest that the bias from unobserved risk characteristics is small also for high LTVs. We split our sample for

[51] This coefficient represents approximately the same size of effect as the benchmark coefficient (i.e. 1 pp Δ in RW $\rightarrow$ 1 bp Δ in interest rate). Median capital requirements in our sample are roughly 12 basis points, so the product of risk weights and capital requirements will be, on average, eight times smaller than risk weights alone. The lower level of the dependent variable implies a larger coefficient by about the same magnitude.

mortgages above and below 75% (the same threshold we used in the benchmark triple difference specification). We find that a 1% increase in risk weights leads to an approximately 2bp increase in rate for high LTV mortgages and 1.5bp for low LTV mortgages. The difference is however not statistically significant.

To account for additional dimensions of risk and confounding stories we perform several robustness tests and a placebo. We show the results in table VI. First we split our sample into two subperiods, which are characterized by different economics conditions. In column (1) we consider the years 2009-2012 in which the economy was recovering from the global financial crisis and was hit by the European sovereign debt crisis. In column (2) we study the period 2012-2015, which was characterized by steady growth and renewed competition in the mortgage market, in particular at high LTV ratios. Despite the different economic environments the coefficients are almost identical in the two periods.

In column (3) we estimate the model on a balanced panel of lenders, to control for possible differences in the pass-through as a result of lenders entering into our sample or dropping out from it. The coefficient remains significant and the magnitude is not statistically different. In all our previous specifications we already control for individual and loan characteristics, to capture some observable dimensions of risk, such as income and age. However, another important dimension of riskiness can be due to local economic conditions that affect the ability of borrowers in a specific location to repay the mortgage balance. To tackle this issue we add in column (4) fixed effects for the postcode-year of the mortgage and the results are not statistically different.

Finally, we address directly the concern that other omitted mechanisms are driving our results. In the last two columns of table VI we focus on a subset of lenders for which we have data on the funding cost. Column (5) reports the main model in equation 3 estimated on this subset of lenders. These lenders seem to have a higher pass-through of risk weights into interest rates. A 1% increase in the risk-weight is now associated with a 2.3bp increase in rates. In column (6) we test if the risk weight pass-through mechanism survives once we control for possible differential effect of funding costs on lending rates. We implement this placebo by interacting time-varying funding cost data with a dummy for low LTV mortgages. If lenders with higher funding costs have different risk-taking strategies and therefore price low and high LTV mortgages differently from lenders with low funding costs we should find a significant coefficient in the interaction term.[52] First, we find that funding costs do not seem to have a significant differential impact on low LTV mortgages. Second, the coefficient on the risk weights in not affected, thus reinforcing our benchmark result.

To summarize, we find that a 1% increase in risk weights increase the interest rate by 1bp on average. The effect is stronger for lenders with low capital buffers, while it does not differ significantly across LTVs and over the Basel II period. The pass-through of risk weights on prices does play an independent role, which is not affected by observable controls for risk or the inclusion of alternative mechanisms.

[52]Within this specification, we cannot estimate the direct impact of funding cost on rates, given that the mean effect is captured by the lender-time dummies.

Both the triple difference model exploiting the regime change and the risk weights model within the new regime show that risk weights do affect interest rates. But the implied size of effect is different in each case. Under the triple-difference model, a 12 percentage point risk weight gap drove a 32bp difference in interest rates.[53] This implies that a 1pp difference in risk weight implied approximately a 3bp difference in mortgage rates. Conversely, in the risk weights model we found a smaller effect: a 1pp increase in risk weight was associated with a 1bp increase in price.

This discrepancy in the magnitude can be attributed to a number of factors, of which we consider the following two to be the most important. First, the triple-difference model exploits the introduction of Basel II as an exogenous policy shock. The precipitous fall in mortgage risk weights which followed represented a simultaneous shock to the marginal costs of all lenders in the market (although IRB lenders were more affected than SA lenders). In contrast, the idiosyncratic risk weight variation which underlies our second model is lender-specific and unobserved by other market participants. Theory and evidence from cost pass-through models suggest that market-wide cost shocks have a higher rate of pass-through than private shocks. In this case, both of our estimated coefficients may be accurate, but reflect different scenarios (symmetric vs. idiosyncratic shocks) which induce varying levels of pricing responses by lenders.

Second, there are several reasons why lender behaviour and competitive effects may have changed in the post-crisis, post-Basel II period. These include reforms to bank regulation, low interest rates, and increased competition from challenger banks. Structural changes to the underlying market may affect parameter estimates in our reduced-form models. Despite these differences in the source of identification and in the environment, we find strong similarities in the order of magnitude and the significance of the effects from the two approaches, thus supporting our causal mechanism from changes in risk weights to interest rates.

IV. Conclusions and discussion

Our results evidence the operation of the specialisation hypothesis (Repullo and Suarez, 2004) in the UK mortgage market. The switch to Basel II gave lenders using internal (IRB) models a comparative advantage in capital requirements (compared to lenders using the standardised approach, or SA), particularly at low loan-to-value (LTV) ratios, and this was reflected in prices and quantities. Lenders in general reduced their prices by more for low (versus high) LTV lending. But lenders using IRB did so by 31bp more, and increased their low-LTV portfolio by 11pp more, than lenders using SA. Risk was thus systemically concentrated in SA lenders. Under Basel II, methodology-driven heterogeneity among lenders with internal models was also priced: a 1pp reduction in risk weights caused a 1bp reduction in interest rates. For the typical 30pp IRB-SA risk weight gap at low LTV ratios, this translates to a 30bp price advantage for IRB lenders. For SA lenders this implies a fall by several places on the best-buy table and likely substantial loss of

[53] 12 percentage points is obtained by considering the additional difference (i.e. the larger gap) found between IRB and SA risk weights at low LTV ratios.

market share. This pass-through of risk weights to prices was larger for lenders holding less of a buffer over their capital requirements.

A number of implications – for financial stability, macroprudential policy, and competition policy – flow from our finding that the specialisation mechanism operates in the mortgage market.

First, from a financial stability perspective, the specialisation mechanism causes concentration of mortgage risk in lenders on the standardised approach. Such lenders are likely to have less sophisticated risk management (Rime, 2005). For example, they tend to be smaller and so have less resource to devote to risk management. And they are less likely to have developed risk modelling capabilities to the same level as IRB lenders (if they had such capabilities then they would have had a strong incentive to apply for IRB permission, and would likely have been granted them). Concentration of high LTV mortgages in smaller lenders with less sophisticated risk management may increase the expected average failure rate among the population of lenders, but decrease the probability of failure among systemically important lenders. Whether this is judged to be net beneficial for financial stability depends on the relative value attached to these opposing outcomes. Prudential policies that seek to reduce the variability in capital requirements arising from risk weight methodology would modulate the strength of the specialisation mechanism, depending on how they affect the IRB-SA gap in capital requirements across different exposures. For example, a leverage ratio requirement, where binding, would lead to the same capital requirement across firms and exposures, effectively neutering the IRB-SA gap in risk weights at low LTV[54]; lower SA risk weights for low LTV mortgages (or floors on IRB models) would directly reduce the differential in the IRB-SA gap between high and low LTV; changes in Pillar 2 capital requirements could reduce the IRB-SA gap in terms of total capital requirements; finally, facilitating the adoption of IRB models by a wider range lenders should weaken economic importance of the IRB-SA gap (Woods, 2016). Such policies therefore have financial stability implications via the specialisation mechanism in addition to any other channels identified. In the mortgage market, reducing the comparative advantage conferred by IRB at low LTV ratios could reduce the concentration of high LTV mortgages among smaller lenders, but conversely could lead to large systemic banks taking on riskier exposures.[55]

Second, macroprudential tools may affect the *strength* of the specialisation mechanism. This should be accounted for in calibrating such tools. For example, consider capital buffers for systemic risk (eg for global systemically important banks). These are selectively applied to lenders who also tend to use IRB, thus raising capital requirements across all assets for those lenders. This will reduce the *average* IRB-SA gap. But since capital buffers are expressed as an add-on to the capital *ratio* requirement, increasing them has a multiplicative effect on capital requirements: the absolute increase in capital requirements for IRB lenders will be larger for assets which already have higher IRB risk weights. In the mortgage market, this will reduce the IRB-SA gap in capital requirements by more at high versus low LTV ratio, and so strengthen the specialisation mecha-

[54] See also Competition and Markets Authority (2016).

[55] And if IRB models underestimate risk not only for corporate lending (as evidenced by Behn et al. (2014)) but also for mortgages, then IRB lenders may be less well capitalised than SA lenders.

nism. Furthermore, the procyclicality of internal models versus the acyclicality of the standardised approach, means that the relative size of the gap between SA and IRB risk weights at low versus high LTV ratios, and thus the strength of the specialisation mechanism, is also procyclical (Behn et al., 2016). Indeed, the strength of the specialisation mechanism will be affected by anything which changes the methodology-driven heterogeneity in capital requirements between lenders in a way that systematically differs across different classes of risk exposure.

Third, competition authorities have identified the cost of adopting IRB as a potential barrier to entry and expansion (Competition and Markets Authority, 2015; Financial System Inquiry, 2014). The barrier would arise from the combination of high cost of IRB adoption and the comparative advantage induced by the methodology-driven heterogeneity in risk weights between IRB and SA lenders. Our evidence is consistent with IRB providing a competitive advantage in low LTV ratio mortgages.

Finally, the specialisation mechanism, as originally theorised, is not specific to the mortgage market. Evidence for the operation of the specialisation mechanism in the mortgage market then should raise prior expectations that it also operates in other markets. Testing this for other markets, perhaps by adapting the identification strategy developed in this paper, could be a fruitful direction for future research.

Our estimated effect sizes can be used in assessing the contribution of the specialisation mechanism to the overall impact of macro- and micro-prudential tools, and thus in the calibration of these tools. (Application of estimates is of course subject to the Lucas critique.) To the extent that application of the tools does not represent too radical a departure from Basel II risk weights, our approximation may be reasonable.[56] And given that the pass-through of symmetric cost shocks is thought to be higher than pass-through of asymmetric shocks (RBB Economics, 2014), our estimates could be used as a lower bound on the true effect of macro-prudential policies.

[56]The pass-through of risk weights to prices is a consequence of bank behaviour. We do not have a structural model to determine bank behaviour under circumstances different to those observed in our data, but loosely speaking the external validity of our estimates depends on the assumption that behaviour will be similar in the counterfactual of interest. This assumption seems more plausible for counterfactuals that retain the qualitative features of our data, notably that the IRB-SA risk weight gap is larger at lower LTV ratios, and for counterfactuals that represent relatively small perturbations from the risk weights observed in our data.

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Appendix A. Figures

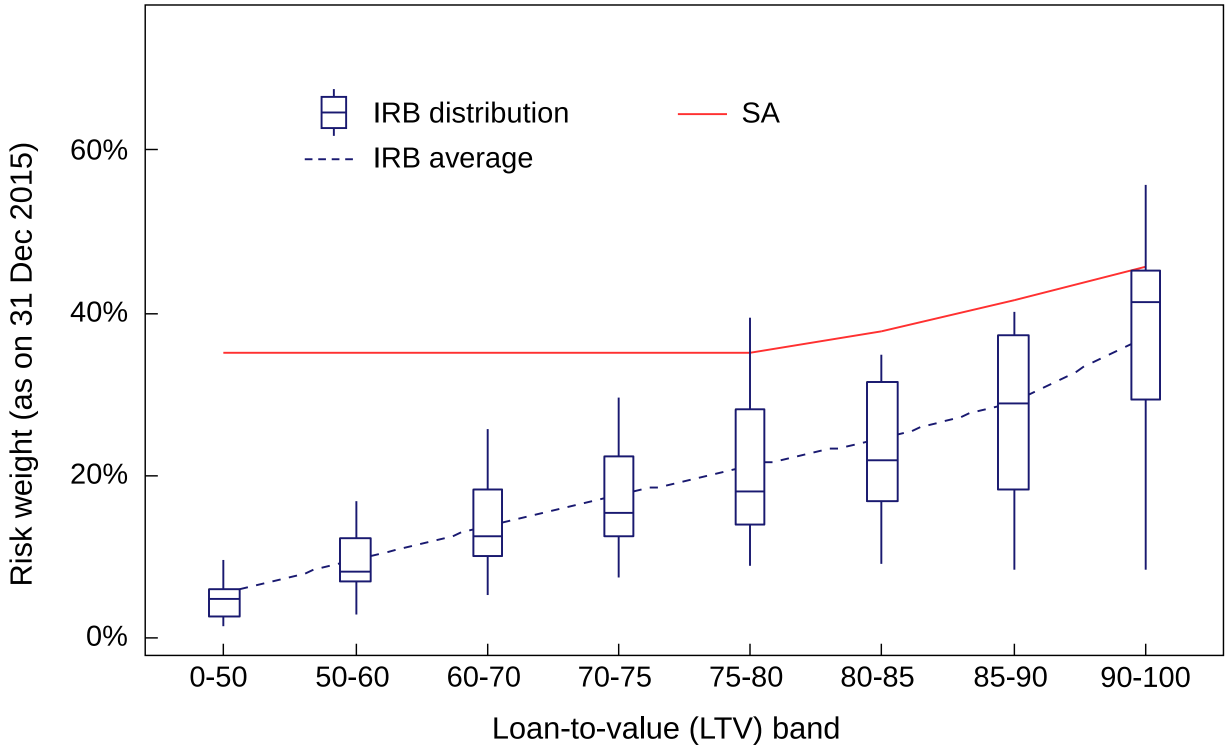


Figure 1. Risk weight distribution.
The figure shows the gap in risk-wights. The distributions of IRB risk weights within each LTV band are represented by Tukey boxplots, where the box represents the interquartile range (IQR) and the whiskers represent the most extreme observations still within 1.5 * IQR of the upper/lower quartiles

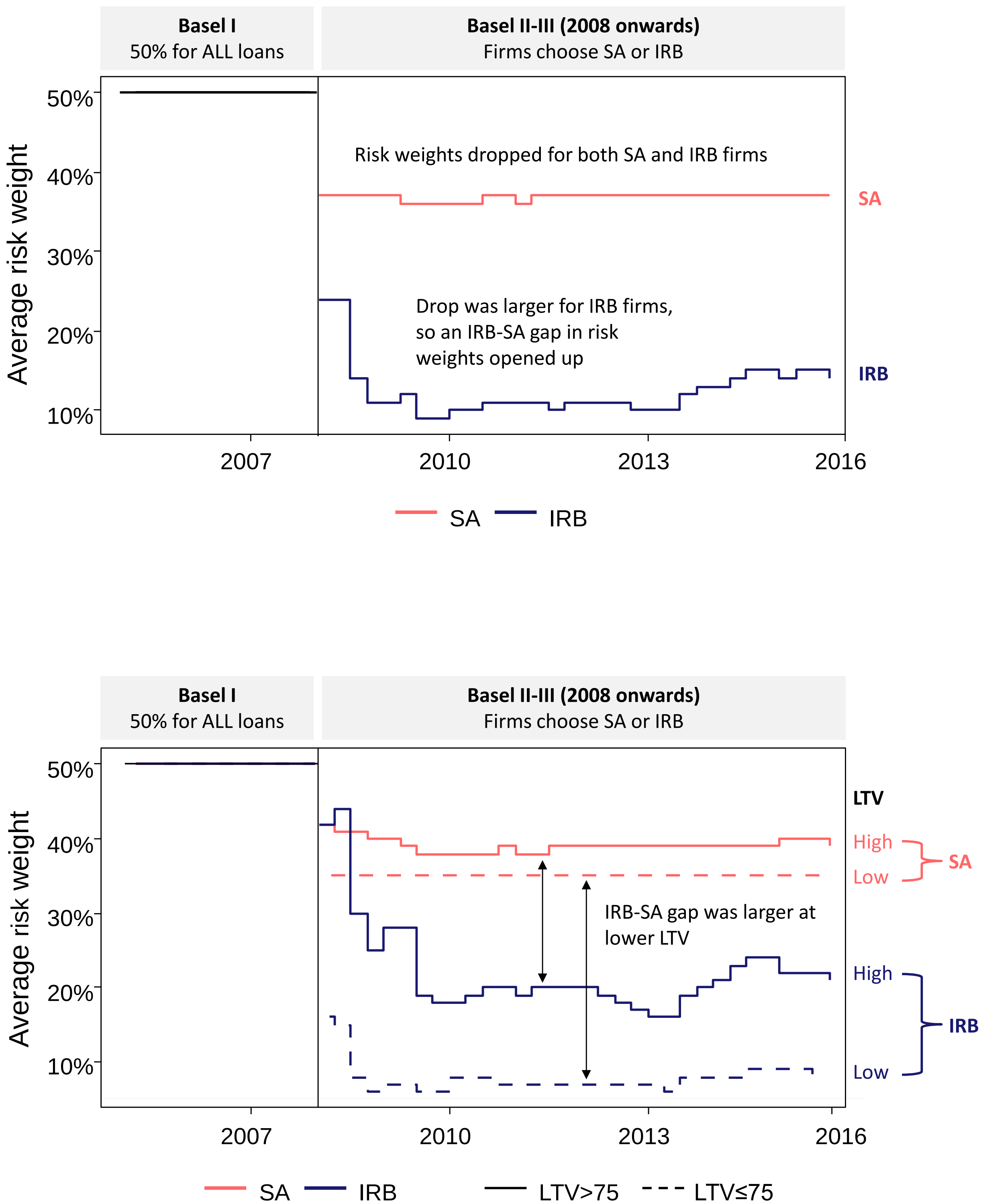
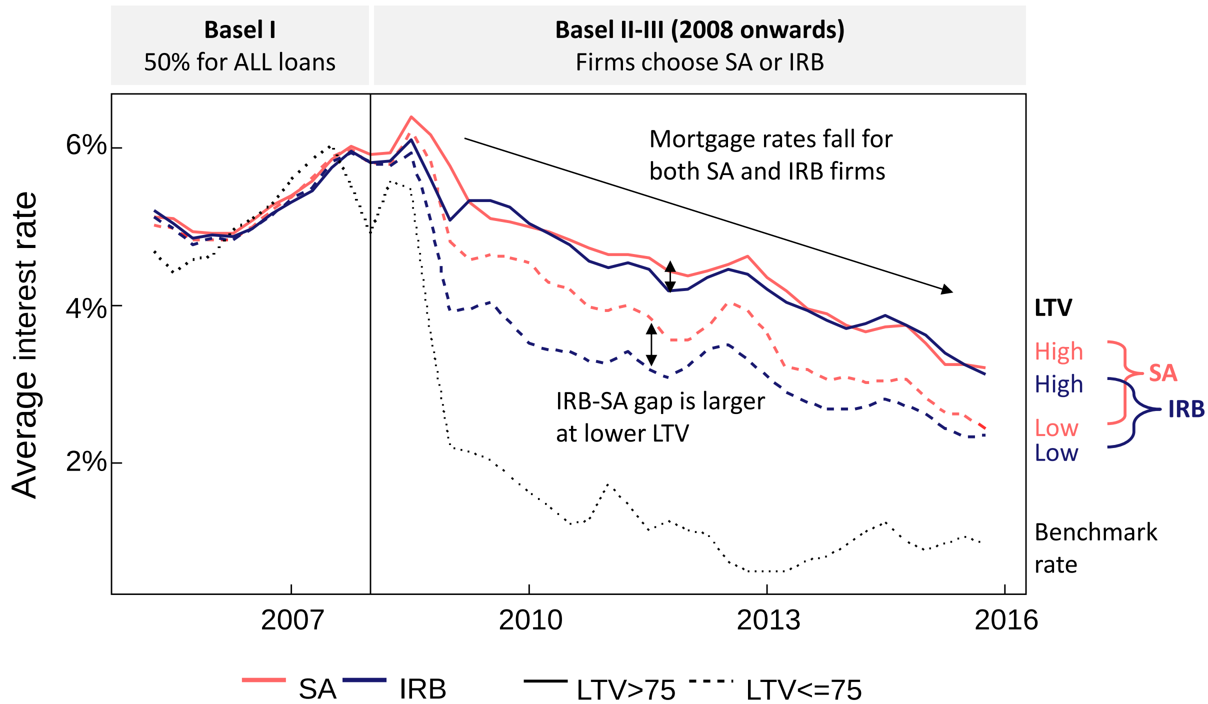


Figure 2. Triple difference: risk weights.
The figure shows the dynamics of risk weights in the period 2005-2015



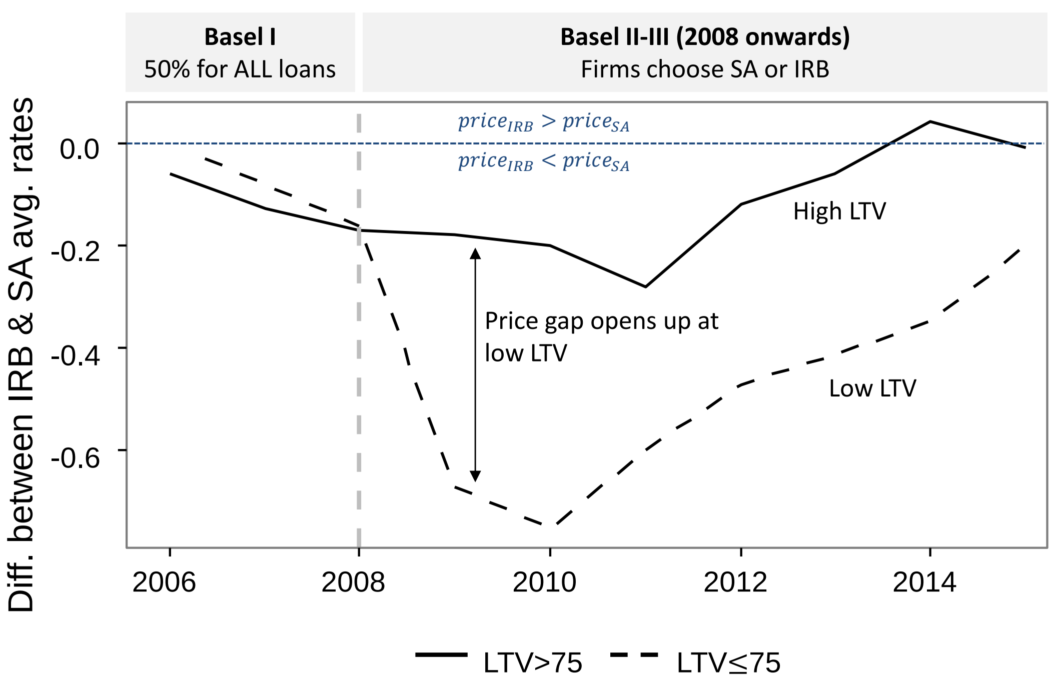


Figure 3. Triple difference: mortgage rates.
The figure shows the dynamics of mortgage rates in the period 2005-2015

Appendix B. Tables

Table I – Summary statistics.
The table shows the summary statistics for the different samples that we use in our empirical analysis. We report the mean and the standard deviation (in parenthesis). Column (1) shows our full sample. Column (2), the sample used to estimate the DDD model, follows the cleaning steps outlined in this paper. The majority of exclude observations between (1) and (2) are due to missing interest rate data. Column (3) is similar to (1), but restricted to the time period over which we estimate the RW model. Column (4) represents the final sample used to estimate the RW model after all cleaning steps.

	(1) Full PSD	(2) DDD model	(3) Full PSD (2009-15)	(4) RW model
Panel A: mortgage characteristics				
Interest rate	0.042	0.042	0.034	0.034
	(0.013)	(0.013)	(0.011)	(0.011)
LTV	62.8%	61.7%	63.6%	62.9%
	(22.6)	(22.7)	(22.0)	(22.0)
Loan value	139,232.3	141,762.2	147,148.9	151,515.0
	(98,224.8)	(100,302.2)	(103,862.0)	(106,668.2)
Maturity	21.7	21.4	22.2	21.9
	(8.0)	(7.3)	(8.9)	(7.7)
Fraction fixed	69.4%	70.0%	75.7%	75.1%
Fraction interest only	23.1%	21.9%	12.8%	12.5%
Panel B: borrower characteristics				
Property value	235,649	244,296	247,335	257,496
	(173,302)	(179,397)	(189,157)	(195,622)
Age	38.9	39.3	38.9	39.1
	(10.0)	(10.1)	(10.1)	(10.0)
Income	52,576	53,790	54,588	56,522
	(39,614)	(40,348)	(40,213)	(41,270)
LTI	2.84	2.82	2.88	2.86
	(1.05)	(1.05)	(1.08)	(1.08)
Fraction impaired	0.8%	0.7%	0.3%	0.2%
Fraction joint	51.3%	51.4%	49.5%	48.5%
Fraction income verified	66.7%	70.2%	77.4%	81.8%
Fraction FTB	21.3%	20.2%	26.7%	24.9%
Fraction remortgagors	43.3%	44.1%	35.7%	36.9%
Panel C: lender characteristics				
No. of lenders	93	85	81	73
No. of lender-quarters	2,998	2,502	1,842	1,502
No. of IRB lenders	19	17	17	14
Share of IRB loans	90.0%	86.8%	91.2%	88.8%
Risk weight	0.288	0.275	0.133	0.140
	(0.198)	(0.195)	(0.111)	(0.116)
No. observations	9,955,746	6,957,841	5,330,777	3,862,944

Table II Triple difference model: benchmark.

The three panels show the results from, respectively, specifications defined in equations 1 and 2, as well as a third specification using arrears rates as the dependent variable. 'Low LTV' in the benchmark specification is defined as LTV below or equal to 75%. The Basel I period includes all mortgages between 2005 Q2 and 2007 Q4, while the Basel II period lies between 2008 Q1 until 2015 Q4. In panel A, the dependent variable is the loan-level interest rate to borrower i from lender l in LTV band b in period t. In panel B, the dependent variable is the share for lender l of mortgages in LTV band b in period t. In panel C, the dependent variable is a dummy equal to one if mortgage i from lender l in LTV band b issued in period t is in arrear in 2011. DDD_{lbt} is the coefficient on the triple interaction: $BaselII_t \times IRB_l \times LowLTV_b$. All standard errors are clustered at the lender-quarter level.

	Benchmark	LTV threshold		Subperiods		Balanced panel	FE: Geo	FE: full
	75%	70%	80%	0506-0910	0506-1011			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: interest$_{ilbt}$								
DDD_{lbt}	-0.319***	-0.463***	-0.272***	-0.699***	-0.373***	-0.348***	-0.396***	-0.262***
	(0.088)	(0.083)	(0.090)	(0.125)	(0.121)	(0.128)	(0.062)	(0.038)
Adjusted R2	0.401	0.384	0.410	0.450	0.592	0.358	0.709	0.785
Observations	6,931,773	6,931,773	6,931,773	2,447,601	2,595,129	2,299,047	6,886,045	6,931,739
Panel B: portfolio share$_{lbt}$								
DDD_{lbt}	0.121***	0.110***	0.101***	0.151***	0.151***	0.158***		0.124***
	(0.008)	(0.008)	(0.009)	(0.014)	(0.012)	(0.016)		(0.008)
Adjusted R2	0.077	0.092	0.065	0.121	0.110	0.077		0.482
Observations	19,571	19,571	19,571	6,964	7,178	11,503		19,504
Panel C: arrears$_{ilbt}$								
DDD_{lbt}	0.039***	0.046***	0.045***	0.063***	0.095***	-0.046**	0.061***	0.025**
	(0.014)	(0.014)	(0.017)	(0.018)	(0.020)	(0.024)	(0.017)	(0.011)
Adjusted R2	0.036	0.037	0.036	0.053	0.028	0.027	0.046	0.061
Observations	659,953	659,953	659,953	438,826	239,636	40,711	655,432	659,861

Table III Triple difference model: horse-race triple interactions.
The three panels show the results from model 1 enriched with additional interaction terms. Low LTV_b is a dummy equal to one for mortgages with LTV below or equal to 75%. Basel II_t is a dummy equal to one between 2008 Q1 until 2015 Q4. The dependent variable is the loan-level interest rate to borrower i from lender l in LTV band b in period t. Column (1) show the benchmark model, as in panel A column (1) of table II. Low $buffer_l$ is a dummy for lenders whose capital buffer at the end of 2007 was below the median. Funding $shock_l$ is a dummy for lenders that experienced an above-average increase in funding cost for term unsecured debt after 2008. All standard errors are clustered at the lender-quarter level.

	Dependent variable: $interest_{ilbt}$			
	(1)	(2)	(3)	(4)
Basel II_t × Low LTV_b×				
IRB_l	-0.319***		-0.450***	
	(0.088)		(0.086)	
Low $buffer_l$		0.086	0.079	
		(0.090)	(0.092)	
Funding $shock_l$				-0.027
				(0.118)
Adjusted R2	0.401	0.397	0.405	0.401
Observations	6,931,773	6,931,773	6,931,773	5,032,264

Table IV Risk weights model: benchmark.

The table show the results from, respectively, specifications defined in equations 3 and 4, as well as a third specification interacting risk weights with capital resources. The dependent variable is the loan-level interest rate to borrower i from lender l in LTV band b in period t. RW_{lbt} is the risk weight for lender l in LTV band b in period t. $Capreq_{lt}$ is the lender specific capital requirement in period t. Total capital requirements include both minimum requirements under Basel II (Pillar I, or 8% of RWAs) as well as lender-specific supervisory add-ons (Pillar II). $Capres_{lt}$ is the lender specific capital resources in period t. Total capital resources include all classes of regulatory capital, including Common Equity Tier 1, Additional Tier 1, and Tier 2. All standard errors are clustered at the lender-quarter level.

	Dependent variable: interest_{ilbt}		
	(1)	(2)	(3)
RW_{lbt}	0.010***		
	(0.003)		
$RW_{lbt} \times \text{Cap req}_{lt}$		0.060***	
		(0.018)	
$RW_{lbt} \times \text{Cap res}_{lt}$			0.034***
			(0.011)
Fixed effects:			
Lender-quarter	Yes	Yes	Yes
Lender-band	Yes	Yes	Yes
Band-quarter	Yes	Yes	Yes
Individual controls	Yes	Yes	Yes
Adjusted R2	0.636	0.633	0.633
Observations	3,748,593	3,696,374	3,696,374

Table V Risk weights model: heterogeneity.

The table show the results from, respectively, specifications defined in equations 3, in subsamples of the data. The dependent variable is the loan-level interest rate to borrower i from lender l in LTV band b in period t. RW_{lbt} is the risk weight for lender l in LTV band b in period t. Low capital buffer is defined as total capital resources being less than or equal to 6 percentage points above total capital requirements (both resources and requirements expressed as a ratio of risk-weighted assets). Low LTV is defined as an LTV ratio below or equal to 75%. All standard errors are clustered at the lender-time level.

	Dependent variable: interest_{ibst}					
	Methodology		Capital buffer		LTV	
	IRB	SA	High	Low	High	Low
	(1)	(2)	(3)	(4)	(5)	(6)
RW_{lbt}	0.011***	-0.006	0.001	0.017***	0.019***	0.014***
	(0.003)	(0.005)	(0.003)	(0.004)	(0.005)	(0.003)
Fixed effects:						
Lender-quarter	Yes	Yes	Yes	Yes	Yes	Yes
Lender-band	Yes	Yes	Yes	Yes	Yes	Yes
Band-quarter	Yes	Yes	Yes	Yes	Yes	Yes
Individual controls	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R2	0.622	0.708	0.710	0.563	0.671	0.533
Observations	3319772	428821	2244041	1490925	1177934	2570659

Table VI Risk weights model: robustness.

The table show the results from specification defined in equations 3, in different sub-samples of the data and with additional controls. The dependent variable is the loan-level interest rate to borrower i from lender l in LTV band b in period t. RW_{lbt} is the risk weight for lender l in LTV band b in period t. In column (1) and (2) we consider the years 2009-2012 and 2012-2015, respectively. In column (3) we limit the analysis to a balanced panel of lenders. In column (4) we include postcode-year fixed effects. In column (5) and (6) we limit the analysis to lenders for which we have funding cost data. Low LTV_b is a dummy equal to one for mortgages with LTV below or equal to 75%. All standard errors are clustered at the lender-time level.

	Dependent variable: $interest_{ibst}$					
	Subperiods		Balanced panel	Geography	Other channel	
	(1)	(2)	(3)	(4)	(5)	(6)
RW_{lbt}	0.010***	0.011***	0.009***	0.007***	0.023***	0.023***
	(0.003)	(0.003)	(0.004)	(0.003)	(0.005)	(0.005)
Funding $cost_{lt}$ × $LowLTV_b$						0.006
						0.003
Fixed effects:						
Lender-quarter	Yes	Yes	Yes	Yes	Yes	Yes
Lender-band	Yes	Yes	Yes	Yes	Yes	Yes
Band-quarter	Yes	Yes	Yes	Yes	Yes	Yes
Individual controls	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R2	0.646	0.633	0.585	0.635	0.584	0.584
Observations	3748593	2331956	1912261	2371864	2392471	2392471

Appendix C. Additional material

In this section we show the decomposition of the results of the triple difference model. Several results emerge from an overall comparison on interest rates in Table VII. First, the average interest rate for IRB lenders is *always* below the one by SA lenders, except in during Basel I for low LTVs in which they are very similar. This result can be due to an absolute cost advantage for IRB lenders, which are mostly larger banks with large economies of scale, and this is reflected in pricing of both high and low LTV mortgages. Second, the average interest rate on low LTV mortgages is *always* below the one for high LTV mortgages. This result is attributable to the fact that high LTV mortgages are riskier than low LTV ones and the higher rates is therefore reflecting the higher risk. Third, during Basel I the differences between high and low LTV are smaller than during Basel II and this holds for both type of lenders.

Table VII Triple difference model: Interest rates.
The table shows the results from specification 1 without any additional controls. The low LTV is defined as LTV below or equal to 75%. The Basel I period includes all mortgages between 2005Q2 and 2007 Q4, while the Basel II period is between 2008 Q1 until 2014 Q4. P-values are given in parentheses.

	Basel I		Basel II	Δ Basel II - Basel I
Panel A: Low LTV				
IRB	5.21		3.42	-1.79
SA	5.20		3.94	-1.26
Δ SA-IRB	-0.01		0.52	
	(0.00)		(0.00)	
DD		-0.53		
		(0.00)		
Panel B: High LTV				
IRB	5.24		4.21	-1.02
SA	5.29		4.40	-0.89
Δ SA-IRB	0.06		0.19	
	(0.00)		(0.00)	
DD		-0.13		
		0.36		
DDD				
		-0.40		
		(0.00)		

We now explain how we isolate the effect of risk weights on interest rate with the triple difference model. First, in panel A of Table VII we show the average interest rate for the "treatment" category: low LTV mortgages. Each cell contains the mean interest rates for the IRB and SA lenders in the two period we analyse. Interest rates fall (from Basel I to Basel II) for both IRB and SA lenders.

This common effect is driven by the decrease in the policy rate following the global financial crisis. The fall in interest rates for low LTV mortgages is larger for IRB lenders than for SA lenders, 179bp and 116bp respectively. As a result, we find a 53bp relative fall in the interest rates of low LTV mortgages for lenders adopting IRB models and the effect is statistically significant. This result is the difference in difference estimate of the impact of IRB models. As we describe in the identification strategy there can be lenders specific shock contemporaneous to the introduction of IRB models, thus biasing our estimates when we look only at the first-difference.

In Panel B of Table VII we show the differences in the average rates for the "control" category: high LTV mortgages. Interest rates falls moving from Basel I to Basel II for both IRB and SA lenders also in high LTV mortgages. In this case, the fall in interest rates is larger for SA lenders than for IRB lenders by 13bp. The effect is however not statistically significant.

Taking the difference between the differences in low and high LTV mortgages we are able to isolate the effect of risk weights on interest rates. The third level interaction captures all the variation in interest rate specific to IRB lenders (relative to SA lenders) in low LTV mortgages (relative to high LTV) in the years after the introduction of Basel II (relative to Basel I). The coefficient in TableVII indicates a statistically significant decrease by 40bp in the relative interest rate of low LTV issued by IRB lenders, compared to the change in relative interest rate of high LTV.

In Table VIII we look at portfolio shares, to show the effect of risk weights on lenders' specialization. To achieve this, we compute for each lender in our sample the shares of mortgages for each quarter in each LTV band. In panel A we show the average portfolio share for low LTV mortgages. Each cell contains the mean portfolio share for the IRB and SA lenders in the two periods we analyse. The change from Basel I to Basel II IRB lenders increase their average share in low LTV mortgages by about 1%, while SA lenders decrease their exposure to low LTV mortgages by almost 4%. As a result, we find a 5% relative increase for lenders adopting IRB models in their portfolio shares on low LTV mortgages and the effect is statistically significant. This result is the difference in difference estimate of the impact of IRB models on lenders' portfolio shares.

In Panel B of Table VIII we show the differences in the average portfolio share for the "control" category: high LTV mortgages. IRB lenders decreased their portfolio shares in high LTV mortgages during Basel II relative to Basel I by about 1%. During the same period SA lenders increase their portfolio share in the high LTV category by about 6%. As a result of these trends, IRB lenders decrease on average their relative portfolio share in the high LTV sector. We find a significant difference in difference estimate equal to -7%.

Taking the difference between the differences in low and high LTV mortgages we are able to isolate the effect of risk weights on portfolio shares. The third level interaction captures all the variation in portfolio shares specific to IRB lenders (relative to SA lenders) in low LTV mortgages (relative to high LTV) in the years after the introduction of Basel II (relative to Basel I). The coefficient in TableVIII shows a statistically significant increase by 12% in the relative portfolio share for low LTV by IRB lenders, compared to the change in relative portfolio share of high LTV.

Table VIII Triple difference model: Portfolio shares.
The table shows the results from specification 2. The low LTV is defined as LTV below or equal to 75%. The Basel I period includes all mortgages between 2005Q2 and 2007 Q4, while the Basel II period is between 2008 Q1 until 2014 Q4. P-values are given in parentheses.

	Basel I		Basel II	Δ Basel II - Basel I
Panel A: Low LTV				
IRB	0.15		0.16	0.01
SA	0.21		0.18	-0.04
Δ SA - IRB	0.07		0.02	
	(0.00)		(0.00)	
DD		0.05		
		(0.00)		
Panel B: High LTV				
IRB	0.10		0.09	-0.01
SA	0.09		0.14	0.06
Δ SA - IRB	-0.01		0.05	
	(0.00)		(0.00)	
DD		-0.07		
		(0.00)		
DDD				
		0.12		
		(0.00)		