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NONLINEAR SPILLOVERS BETWEEN EURO AREA SOVEREIGN BOND MARKETS

Summary: This paper examines nonlinear spillover effects between sovereign bond markets of six euro area countries (France, Ireland, Italy, Germany, Portugal, and Spain), four of which were among the hardest hit by the sovereign debt crisis, by applying a nonlinear Granger causality test of Diks and Panchenko (2006). The test is applied on the sovereign bond yield dynamics (i.e. yield changes) time series for the time period from 3 January 2000 – 31 August 2011. We also test for ″pure″ spillovers between sovereign bond yield dynamics, i.e. the spillovers after controlling for common and regional factors that impact the sovereign bond yield changes of all countries simultaneously. To verify if the nature of spillovers has changed after the start of the euro are sovereign debt crisis, we test for the nonlinear spillovers for the whole observed period and separately for the period before and after the start of the euro area sovereign debt crisis (period from the start of April 2010 until the end of our sample, i.e. 31 August 2011). The results of our study show that strong bi-directional Granger causality exists between the investigated sovereign bond markets. Very similar results are obtained whether the regional and world factors are or are not controlled for. We find strong bi-directional non-linear Granger causality for the investigated euro area countries prior the euro area sovereign debt crisis. After the start of the euro area sovereign debt crisis the interdependence between the markets has reduced. We can no longer detect non-linear spillovers running from Germany and France to the ″periphery″ euro area countries. The findings of this study have important implications for the policymakers as they show that shocks spill-over quickly across the sovereign bond markets and the intensity and nature of spillovers can change throughout time. The sovereign bond markets of the ″core″ euro area decoupled from the ″periphery″ euro area sovereign bond markets after the start of euro are debt crisis. The findings are also of relevance for individual investors in the sovereign bond markets for the purpose of portfolio diversification.

Keywords: sovereign bond markets, spillovers, non-linear Granger causality

JEL classification: F21, F36, G15, H63

Introduction

Since the early 2010 euro area sovereign debt crisis has been on the top of the international, especially euro area economic policy agenda. The euro area sovereign debt crisis, triggered by mounting concerns about the public debt sustainability of Mediterranean countries and Ireland quickly spread across (i.e. spilled-over to) the euro area sovereign bond markets, thereby raising the question of public debt sustainability and management and the macroeconomic effects of the sovereign debt crisis. Prompted by financial market pressures, large-scale fiscal austerity measures have been announced in practically all monetary union member states.

The knowledge of the size and nature of exposure of sovereign bond to market spillovers can help policymakers gain insight into public financing constraints and the external risks faced by national economy and their economic agents (Metiu, 2011). This knowledge is relevant also for private financial market participant. Since the works of Markowitz (1952) and empirical evidence of Grubel (1968) financial practitioners adhere to international diversification in order to reduces total risk of their international portfolio(s). When spillovers occur, the dependence between the returns of assets increases and the advantages of international diversification of investment portfolio reduces (Ling and Dhesi, 2010). Rational investors shall respond to changing patterns in dependence by adjusting their portfolios (Savva and Aslanidis, 2010).

The most frequently applied methods in the literature on financial markets interdependence include the vector autoregressive (VAR) models, Granger causality tests (Malliaris and Urrutia, 1992, Gilmore and McManus, 2002), GARCH models (Tse and Tsui, 2002; Bae et al., 2003; Égert and Kočenda, 2010; Mazin et al., 2010; Dajcman, 2012), regime switching models (Garcia and Tsafack, 2009; Schwender, 2010), and wavelet analysis (Dajcman, 2013a). All of these assume linear dependence between the markets and might not capture real dependence, especially in the presence of extreme market movements.

One way to test for potential nonlinear spillovers between sovereign bond markets is to apply a nonlinear Granger causality test. The conventional approach of testing for Granger causality is to assume a parametric, linear time series model, which, however, have low power against certain nonlinear alternatives, like for instance the Hiemstra and Jones (1994) modified version of the Baek and Brock's (1992) test. This test can be used to detect nonlinear Granger-causal relationship between variables in the model, but as showed by Diks and Panchenko (2005, 2006) has certain weaknesses: it can severely over-reject if the null hypothesis of non-causality is true. Diks and Panchenko (2006) therefore proposed a new nonparametric test for Granger causality that will be in a short form presented in the paper. To our best knowledge, there are no empirical studies in the literature that used this method to test for nonlinear Granger causality (spillover) between sovereign bond markets.

This paper aims to test for the possible nonlinear spillover effects between sovereign bond markets of six euro area countries (France, Ireland, Italy, Germany, Portugal, and Spain), four of which were among the hardest hit by the sovereign debt crisis, by applying a nonlinear Granger causality test of Diks and Panchenko (2006). Germany and France are considered as countries of the euro area ″core″ zone, whereas other four countries were at the epicenter of the euro area sovereign debt crisis. The test is applied on the sovereign bond yield dynamics (i.e. yield changes) time series for the time period from 3 January 2000 – 31 August 2011. The existent empirical studies have confirmed that regional and global factors can influence domestic bond markets (Sgherri and Zoli, 2009; Schuknecht *et al.,* 2010; Favero and Missale, 2011; Claeys and Vašiček, 2012). We therefore test also for ″pure″ spillovers between sovereign bond yield dynamics, i.e. spillovers after common and regional factors that impact the sovereign bond yield changes of all countries simultaneously have been controlled for.

In the literature related to this paper, Arezki et al. (2011) investigate whether there were spillover effects of sovereign rating news on European financial markets during the period 2007-2010. They find that sovereign rating downgrades have statistically and economically significant spillover effects both across countries and different segments of financial markets. Balli (2008) investigates the European government bond market integration. He finds that the level of integration has changed during the global financial crisis: while until the start of euro area crisis the sovereign bond markets of euro area seem integrated, during the financial crisis different responses of each euro market to the global shocks reveal that euro bond markets are not fully integrated. Cronefey and Cronon (2013) also find that the spillovers across the euro area sovereign bond markets changed during the sovereign debt crisis. Sgherri and Zoli (2009) in their paper concentrate on euro area sovereign risk premium differentials. They find that ″they tend to comove over time and are mainly driven by a common time-varying factor, mimicking global risk repricing″. From October 2008, however, they find that the euro area markets have become less integrated, as the investors became progressively more concerned about the potential fiscal implications of national financial sectors' fragilty and future debt dynamics. Claeys and Vašiček (2012) analyze spillovers between EU sovereign bond markets. Their results show that there is a lot of heterogeneity in the bilateral spillover sent and received between bond markets. Variance decomposition shows that spillovers are more important than domestic factors for all Eurozone countries. Unlike other studies, they find that spillovers have increased since 2007.

The nature of international dependence and the spillovers between sovereign bond markets in euro area might have changed after the sovereign debt crisis in the euro area erupted. Some countries were hit especially hard, with yields rising few percentage points above the pre-crisis levels (Greece, Portugal, Spain, Italy), whereas others were unaffected (the ″core″ euro area countries) or even benefited as their sovereign bonds became to be perceived as safe havens in period of market turmoil (German sovereign bonds). To verify if the nature of spillovers has changed after the start of the euro are sovereign debt crisis, we test for the nonlinear spillovers for the whole observed period and separately for the period before and after the start of the euro area sovereign debt crisis (period from the start of April 2010 until the end of our sample, i.e. 31 August 2011).

The paper is organized as follows. In the first section following Introduction, we describe the nonlinear Granger causality test of Diks and Panchenko (2006). In the Data and empirical results section we describe the data and provide the results of the econometric nonlinear Granger causality test. The Conclusion section concisely restates the main findings and its implications and provides some ideas for the future research.

Description of the method

The paper applies a nonlinear Granger causality test to verify if the lagged value of one variable significantly explains the present value of another. To explain the method, let us assume that two stationary time series[1] are given, which in a scalar mode can be written as $\{X_t, Y_t, t \geq 1\}$[2]. Variable X Granger causes variable Y if the former´s past and current values statistically significantly predict future values the later. Let $F_{X,t}$ and $F_{Y,t}$ denote the information sets consisting of past observations of X_t and Y_t up to and including time t and ~ denote the equivalence in distribution. $\{X_t\}$ Granger causes $\{Y_t\}$ if for $k \geq 1$

$$(Y_{t+1}, ..., Y_{t+k}) \big| (F_{X,t}, F_{Y,t}) \sim (Y_{t+1}, ..., Y_{t+k}) \big| F_{X,t} . \quad (1)$$

[1] In context of this article, this *would* be two time series of sovereign bond yield changes time series.

[2] For the explanation of Granger causality test we follow Bekiros and Diks (2008) and Dajcman and Festić (2012).

To present a nonlinear nonparametric Granger causality test of Diks and Panchenko (2006), let us introduce delay vectors $\boldsymbol{X}_t^{l_X} = (X_{t-l_X+1},...,X_t)$ and $\boldsymbol{Y}_t^{l_Y} = (Y_{t-l_Y+1},...,Y_t)$, $(l_X, l_Y \geq 1)$. The Granger causality test consists of verifying that the past observations of $\boldsymbol{X}_t^{l_X}$ have no predictive power about Y_{t+1} (beyond that in $\boldsymbol{Y}_t^{l_Y}$):

$$H_0 : Y_{t+1} \left| (\boldsymbol{X}_t^{l_X}; \boldsymbol{Y}_t^{l_Y}) \sim Y_{t+1} \right| \boldsymbol{Y}_t^{l_Y} \ . \tag{2}$$

In a model with two stationary variables, equation (2) reduces to a null hypothesis statement about the invariant distribution of $(\boldsymbol{X}_t^{l_X}, \boldsymbol{Y}_t^{l_Y}, Z_t)$, where $Z_t = Y_{t+1}$. Dropping the time index, and under condition $l_X = l_Y = 1$, the conditional distribution of Z given $(X,Y) = (x,y)$ is the same as that of Z given $Y = y$. Equation (2) can be also be written in terms of a ratio of joint probability density function

$$\frac{f_{X,Y,Z}(x,y,z)}{f_Y(y)} = \frac{f_{X,Y}(x,y)}{f_Y(y)} \cdot \frac{f_{Y,Z}(y,z)}{f_Y(y)} \ . \tag{3}$$

In their paper Diks and Panchenko (2006) prove that this reformulated H_0 implies:

$$q_g \equiv E\left[\left(\frac{f_{X,Y,Z}(X,Y,Z)}{f_Y(Y)} - \frac{f_{X,Y}(X,Y)}{f_Y(Y)} \frac{f_{Y,Z}(Y,Z)}{f_Y(Y)} \right) g(X,Y,Z) \right] = 0 , \tag{4}$$

where $g(X,Y,Z)$ is a positive weight function. For weight function $g(x,y,z) = f_Y^2(y)$ the function reduces to:

$$q \equiv E\left[f_{X,Y,Z}(X,Y,Z) f_Y(Y) - f_{X,Y}(X,Y) f_{Y,Z}(Y,Z) \right] = 0 .$$

Let us now denote $\hat{f}_W(W_i)$ a local density estimator of a d_W -variate random vector $\boldsymbol{W}$ at W_i. The local density estimator is defined as:

$$\hat{f}_W(W_i) = (2\varepsilon_n)^{-d_W} (n-1)^{-1} \sum_{j,j \neq i} I_{ij}^W , \tag{5}$$

where $I_{ij}^W = I(\left\| W_i - W_j \right\| < \varepsilon_n)$, $I(\cdot)$ is indicator function and ε_n the bandwidth.

The test statistic for the non-linear Granger causality test is:

$$T_n(\varepsilon_n) = \frac{n-1}{n(n-2)} \cdot \sum_i (\hat{f}_{X,Z,Y}(X_i,Z_i,Y_i)\hat{f}_Y(Y_i) - \hat{f}_{X,Y}(X_i,Z_i)\hat{f}_{Y,Z}(Y_i,Z_i)) . \tag{6}$$

Under condition $l_X = l_Y = 1$ and $\varepsilon_n = Cn^{-\beta} (C > 0, \frac{1}{4} < \beta < \frac{1}{3})$, Diks and Panchenko (2006) show that the test statistic distribution is:

$$\sqrt{n} \frac{(T_n(\varepsilon_n) - q)}{S_n} \xrightarrow{D} N(0,1) , \tag{7}$$

where $\xrightarrow{D}$ denotes convergence in distribution and S_n is an estimator of the asymptotic variance of $T(\cdot)$ (Diks and Panchenko, 2006).

In order to measure ″pure″ spillovers of sovereign bond yield changes (i.e. its dynamics) between sovereign bonds of different countries, it is important to identify common and regional factors that impact the sovereign bond yield changes of all countries simultaneously (see for instance Forbes and Rigobon (2002) or Dungey et al. (2005)). In order to control for serial correlation in sovereign bond yield changes and any exogenous Eurozone and global shocks we filter the sovereign bond yield changes of a particular country in a similar way that Forbes and Rigobon (2002) suggest (see also Dajcman, 2013b). The specification is:

$$yc_t = \sum_{p=1}^{P} \phi_p yc_{t-p} + \sum_{k=1}^{K} (\alpha_{1k} i_{t-k}^{EZ} + \alpha_{2k} EUROSTOXX_{t-k} + \alpha_{3k} yc_{t-k}^{US} + \alpha_{4k} r_{t-k}^{US}) + \epsilon_t, \quad (8)$$

where is a sovereign bond yield change of the investigated country, is a Eurozone money market interest rate (3-month EURIBOR), is a 10-year U.S. Treasury note yield change, and a return of the Dow Jones Industrial index. and are the number of lags[3]. All variables are calculated as two-day rolling-average values in order to control for the fact of the different open hours of the markets on which the variables in the model are formed. The returns are in the local currency. Following Forbes and Rigobon (2002), five lags () are utilized in order to control for serial correlation and any within-week variation in trading patterns.

To test for the ″pure″ nonlinear spillovers between pairs of sovereign bond markets after controlling for regional and world factors, the residuals of equation (8) are used instead of sovereign bond yield changes.

Data and empirical results

The daily bond yield changes (*yc*) were calculated from the yields (*y*) of central-government bonds (bullet issues) with 10 years maturity. Six euro area countries are considered: France, Ireland, Italy, Germany, Portugal, and Spain. Germany and France are considered as the countries of the euro area ″core″ zone, whereas other four countries were at the epicenter of the euro area sovereign debt crisis. The period of observation is common for all countries and extends from 3 January 2000 – 31 August 2011. Yield changes are calculated from yield as (as for instance in Durré and Pierre (2005) or Dajcman (2012)). Days with no trading in any of the observed markets were left out. The data for bond yields are from Denmark's central bank. Table 1 presents some descriptive statistics of the data.

Table 1 conveys that the greatest daily increases and reductions in sovereign bond yields were recorded in the ″periphery″ euro area countries. The greatest daily increase can be observed for the sovereign bonds of Portugal (a maximum of 30% reduction and 14.5 percent daily increase), followed by Ireland´s (a maximum daily fall of 21.5 percent, and a maximum daily increase of 8.46 percent), Spain´s (a maximum daily fall of 15.8 percent and maximum daily increase of 6.1 percent), and Italy´s sovereign bonds (a maximum daily fall of 14.1 percent and a maximum daily increase of 7.5 percent). The smallest daily changes of yields were recorded for sovereign bonds of France: a maximum daily fall of 4.9 percent and a maximum daily increase of 6 percent during the observed period. All series display significant leptokurtic behavior as

[3] As a proxy for global economic developments the U.S. 10-year Treasury notes yields and Dow Jones Industrial Index returns are added (see, e.g., Forbes and Rigobon, 2002; Dungey et al., 2005; Metiu, 2011). The regional factors are added to capture the local financial market conditions: EUROSTOXX50 return and the EUROBOR 3-month money market rate. As there are interdependencies between different segments of financial markets, Dungey et al. (2007) argued that a particular segment of a financial market should not be studied in isolation.

evidenced by large kurtosis with respect to the Gaussian distribution. The Jarque-Bera test rejects the hypothesis of normal distribution for the observed time series.

Table 1. Descriptive statistics of bond yield changes

	Period of observation	Min	Max	Mean	Std. deviation	Skewness	Kurtosis	Jarque-Bera statistics
France	3 January 2000 – 31 August 2011	-0.04921	0.06003	-0.000220	0.01059	0.1360	4.7921	407.3***
Ireland	3 January 2000 – 31 August 2011	-0.215	0.08457	0.000139	0.01237	-1.3056	38.1730	15,419.9***
Italy	3 January 2000 – 31 August 2011	-0.1406	0.07526	-0.000036	0.00992	-0.6834	19.7355	34,949.3***
Germany	3 January 2000 – 31 August 2011	-0.07596	0.07637	-0.000303	0.01208	0.0345	6.3872	1,422.8***
Portugal	3 January 2000 – 31 August 2011	-0.3006	0.1449	0.0002257	0.01358	-3.3664	93.2459	1.015,175.3***
Spain	3 January 2000 – 31 August 2011	-0.1582	0.06068	-0.000039	0.01101	-1.2329	23.6001	53,357.3***

Notes: Jarque-Bera statistics: *** indicate that the null hypothesis (of normal distribution) is rejected at a 1% significance level.

Source: Own calculations.

The stationarity of bond yield changes was checked by the standard Augmented Dickey-Fuller (ADF) test and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests and the ″efficient″ DF-GLS unit-root test of Elliott et al. (1996)[4] which is more powerful than the standard unit root tests. All the tests lead to conclusion of no unit root in the time series.

In order to evaluate how strong the markets are connected Pearson's correlation coefficients between the logarithmic bond yield changes were calculated (Table 2). Notably, the greatest correlation of bond yield changes in the observed period was achieved between the sovereign bond pairs of France-Germany, and Italy-Spain, while comovement between the yield changes of the sovereign bonds of Germany-Portugal was the smallest of all the investigated sovereign bond market pairs.

Table 2. Pearson's correlation between sovereign bond yield changes

	France	Germany	Ireland	Italy	Portugal	Spain
France	1					
Germany	0.9214	1				
Ireland	0.5277	0.3906	1			
Italy	0.6856	0.5334	0.7063	1		
Portugal	0.4690	0.3288	0.8089	0.6854	1	
Spain	0.6641	0.5286	0.7433	0.9048	0.7299	1

Note: All the correlation coefficients are significantly different from zero.

Source: Own calculations.

The results on the nonlinear Granger causality when the regional and world factors are not controlled for (Table 3) show strong nonlinear causal relationships between the bond yield

[4] The results are not presented in the paper but can be obtained from the author.

changes of investigated euro area countries[5]. The results of this study thus confirm the findings of other existent studies (Sgherri and Zoli, 2009; Schuknecht*et al.*, 2010; Favero and Missale, 2011; Claeys and Vašiček, 2012). Whereas these studies detect strong linear spillovers between the sovereign bond markets, our study identifies also strong nonlinear spillovers between sovereign bond market dynamics.

Mostly, a strong feedback mechanism is identified, implying that shocks from one sovereign bond market spillover to the other and also the opposite. A one-way shock transmission in sovereign bond markets is identified only for the sovereign bond market pairs of Ireland-Italy and Italy-Portugal. Only a shock transmission from the Italian to Ireland's and to Portugal's sovereign bond market is identified, but not in the opposite direction.

Table 3. Nonlinear Granger causality test results – the world and regional factors not controlled for (observation period from 3 January 2000 – 31 August 2011)

	Ireland	Italy	Germany	Portugal	Spain
France	$France \xrightarrow{1\%} Ireland$ $France \xleftarrow{1\%} Ireland$	$France \xrightarrow{5\%} Italy$ $France \xleftarrow{1\%} Italy$	$France \xrightarrow{1\%} Germany$ $France \xleftarrow{1\%} Germany$	$France \xrightarrow{1\%} Portugal$ $France \xleftarrow{1\%} Portugal$	$France \xrightarrow{1\%} Spain$ $France \xleftarrow{1\%} Spain$
Ireland		$Ireland \xrightarrow{No} Italy$ $Ireland \xleftarrow{1\%} Italy$	$Ireland \xrightarrow{1\%} Germany$ $Ireland \xleftarrow{1\%} Germany$	$Ireland \xrightarrow{1\%} Portugal$ $Ireland \xleftarrow{1\%} Portugal$	$Ireland \xrightarrow{1\%} Spain$ $Ireland \xleftarrow{1\%} Spain$
Italy			$Italy \xrightarrow{1\%} Germany$ $Italy \xleftarrow{1\%} Germany$	$Italy \xrightarrow{1\%} Portugal$ $Italy \xleftarrow{No} Portugal$	$Italy \xrightarrow{1\%} Spain$ $Italy \xleftarrow{5\%} Spain$
Germany				$Germany \xrightarrow{1\%} Portugal$ $Germany \xleftarrow{1\%} Portugal$	$Germany \xrightarrow{1\%} Spain$ $Germany \xleftarrow{1\%} Spain$
Portugal					$Portugal \xrightarrow{1\%} Spain$ $Portugal \xleftarrow{1\%} Spain$

Notes: The Granger causality direction is indicated by the direction of the arrow. The number above the arrow indicates the level of significance of rejection of the null of the Diks and Panchenko test. If no Granger causality is observed this is indicated by word No above the arrow. The parameters for the nonlinear Granger causality test is set according to Diks and Panchenko (2006): C=7.5 and $\beta = 2/7$, the bandwidth is $\varepsilon_{2975} = 0.76$.

Source: Own calculations.

The results on the nonlinear Granger causality when the regional and world factors are controlled for, i.e. when the residual sovereign bond yield changes of equation (8) are applied in the nonlinear Granger causality test of Diks and Panchenko (2006), also indicate strong nonlinear Granger causal relationships between the sovereign bond yields (Table 4).

[5] The non-linear causality was tested by the code of Diks and Panchenko (2006).

Table 4: Nonlinear Granger causality test results when controlling for world and regional factors (observation period from 3 January 2000 – 31 August 2011)

	Ireland	Italy	Germany	Portugal	Spain
France	$France \xrightarrow{1\%} Ireland$ $France \xleftarrow{1\%} Ireland$	$France \xrightarrow{1\%} Italy$ $France \xleftarrow{1\%} Italy$	$France \xrightarrow{1\%} Germany$ $France \xleftarrow{1\%} Germany$	$France \xrightarrow{1\%} Portugal$ $France \xleftarrow{1\%} Portugal$	$France \xrightarrow{1\%} Spain$ $France \xleftarrow{1\%} Spain$
Ireland		$Ireland \xrightarrow{5\%} Italy$ $Ireland \xleftarrow{1\%} Italy$	$Ireland \xrightarrow{1\%} Germany$ $Ireland \xleftarrow{1\%} Germany$	$Ireland \xrightarrow{1\%} Portugal$ $Ireland \xleftarrow{1\%} Portugal$	$Ireland \xrightarrow{1\%} Spain$ $Ireland \xleftarrow{1\%} Spain$
Italy			$Italy \xrightarrow{1\%} Germany$ $Italy \xleftarrow{1\%} Germany$	$Italy \xrightarrow{1\%} Portugal$ $Italy \xleftarrow{5\%} Portugal$	$Italy \xrightarrow{1\%} Spain$ $Italy \xleftarrow{1\%} Spain$
Germany				$Germany \xrightarrow{1\%} Portugal$ $Germany \xleftarrow{1\%} Portugal$	$Germany \xrightarrow{1\%} Spain$ $Germany \xleftarrow{1\%} Spain$
Portugal					$Portugal \xrightarrow{1\%} Spain$ $Portugal \xleftarrow{1\%} Spain$

Notes: The Granger causality direction is indicated by the direction of the arrow. The number above the arrow indicates the level of significance of rejection of the null of the Diks and Panchenko test. If no Granger causality is observed this is indicated by word No above the arrow. The parameters for the nonlinear Granger causality test is set according to Diks and Panchenko (2006): C=7.5 and $\beta = 2/7$, the bandwidth is $\varepsilon_{2975} = 0.76$.

Source: Own calculations.

It is interesting to note that now strong bi-directional spillovers between all pairs of sovereign bond markets are observed. Whereas when regional and world factors were not controlled for only a one-directional spillovers were detected between sovereign bond markets of Ireland-Italy and Italy-Portugal, now a significant (at a 5% level) bi-directional spillovers are identified.

As already noted, the nature of international dependence and the spillovers between sovereign bond markets in euro area might have changed after the sovereign debt crisis in the euro area erupted. To verify this, we test for the nonlinear spillovers separately for the period before the euro area sovereign debt crisis (period from the start of 2000 until the end March 2010) and separately for the period after the start of the euro area sovereign debt crisis (period from the start of April 2010 until the end of our sample, i.e. 31 August 2011)[6].

The results for the first sub-period are presented in Table 5. We find that prior the sovereign debt crisis spillovers between the investigated sovereign bond markets were present. For all but one pair (namely, France-Ireland) we find significant nonlinear Granger causality. This implies that the sovereign bond markets (when yield dynamics is regarded) were fairly connected.

[6] Greece requested EU and IMF for a bailout on April 23, 2010. The expectations of this event however culminated throughout the month.

Table 5: Nonlinear Granger causality during prior the sovereign debt crisis in euro area

	Ireland	Italy	Germany	Portugal	Spain
France	$France \xrightarrow{1\%} Ireland$ $France \xleftarrow{10\%} Ireland$	$France \xrightarrow{1\%} Italy$ $France \xleftarrow{5\%} Italy$	$France \xrightarrow{1\%} Germany$ $France \xleftarrow{1\%} Germany$	$France \xrightarrow{1\%} Portugal$ $France \xleftarrow{1\%} Portugal$	$France \xrightarrow{5\%} Spain$ $France \xleftarrow{1\%} Spain$
Ireland		$Ireland \xrightarrow{5\%} Italy$ $Ireland \xleftarrow{1\%} Italy$	$Ireland \xrightarrow{1\%} Germany$ $Ireland \xleftarrow{1\%} Germany$	$Ireland \xrightarrow{1\%} Portugal$ $Ireland \xleftarrow{1\%} Portugal$	$Ireland \xrightarrow{5\%} Spain$ $Ireland \xleftarrow{1\%} Spain$
Italy			$Italy \xrightarrow{1\%} Germany$ $Italy \xleftarrow{1\%} Germany$	$Italy \xrightarrow{1\%} Portugal$ $Italy \xleftarrow{1\%} Portugal$	$Italy \xrightarrow{5\%} Spain$ $Italy \xleftarrow{1\%} Spain$
Germany				$Germany \xrightarrow{1\%} Portugal$ $Germany \xleftarrow{1\%} Portugal$	$Germany \xrightarrow{5\%} Spain$ $Germany \xleftarrow{1\%} Spain$
Portugal					$Portugal \xrightarrow{1\%} Spain$ $Portugal \xleftarrow{1\%} Spain$

Notes: The world and regional factors are controlled for. The observation period is from 3 January 2000 – 31 March 2010. The Granger causality direction is indicated by the direction of the arrow. The number above the arrow indicates the level of significance of rejection of the null of the Diks and Panchenko test. If no Granger causality is observed this is indicated by word No above the arrow. The bandwidth is $\varepsilon = 0.79$. See also the notes for Table 4.

Source: Own calculations.

Table 6 conveys the results of nonlinear Granger causality tests for the period of sovereign debt crisis in euro area. Clearly, the interdependence between the markets has reduced. The results are thus in line with those of Arezki et al. (2011), Balli (2008), Cronefey and Cronon, and Sgherri and Zoli (2009). We can no longer detect nonlinear spillovers running from Germany and France to the ″periphery″ euro area countries. The opposite is true, especially spillovers from Italy and Ireland to the ″core″ euro area were observed, whereas spillovers from the Portugal and Spain to the ″core″ of euro area are either not significant or not highly significant. A sort of ″decoupling″ of dynamics in the ″core″ from the ″periphery″ euro area sovereign bond markets can be observed.

The findings of this study have relevant implications for two groups of economic agents: economic policy makers and financial market investors. As the shocks in sovereign bond markets can swiftly spill-over from one to another country, economic policy that reassures confidence of investors in sovereign debt market is necessary in case of negative spillovers. The results for the two sub-periods show that the interdependence can change throughout time. The sovereign bond markets of the ″core″ euro area decoupled from the ″periphery″ euro area sovereign bond markets. While in the former the required yields to maturity decreased in the later they increased due to uncertainty about the sustainability of public debt. The measures that reassured the sovereign bond markets in the ″periphery″ therefore were appropriate.

Table 6: Nonlinear Granger causality during the sovereign debt crisis in euro area

	Ireland	Italy	Germany	Portugal	Spain
France	France $\xrightarrow{10\%}$ Ireland France $\xleftarrow{1\%}$ Ireland	France $\xrightarrow{No}$ Italy France $\xleftarrow{1\%}$ Italy	France $\xrightarrow{1\%}$ Germany France $\xleftarrow{1\%}$ Germany	France $\xrightarrow{No\%}$ Portugal France $\xleftarrow{10\%}$ Portugal	France $\xrightarrow{No}$ Spain France $\xleftarrow{5\%}$ Spain
Ireland		Ireland $\xrightarrow{5\%}$ Italy Ireland $\xleftarrow{5\%}$ Italy	Ireland $\xrightarrow{1\%}$ Germany Ireland $\xleftarrow{10\%}$ Germany	Ireland $\xrightarrow{10\%}$ Portugal Ireland $\xleftarrow{5\%}$ Portugal	Ireland $\xrightarrow{5\%}$ Spain Ireland $\xleftarrow{5\%}$ Spain
Italy			Italy $\xrightarrow{1\%}$ Germany Italy $\xleftarrow{No}$ Germany	Italy $\xrightarrow{No}$ Portugal Italy $\xleftarrow{No}$ Portugal	Italy $\xrightarrow{1\%}$ Spain Italy $\xleftarrow{No}$ Spain
Germany				Germany $\xrightarrow{No}$ Portugal Germany $\xleftarrow{10\%}$ Portugal	Germany $\xrightarrow{No}$ Spain Germany $\xleftarrow{5\%}$ Spain
Portugal					Portugal $\xrightarrow{No}$ Spain Portugal $\xleftarrow{No}$ Spain

Notes: The world and regional factors are controlled for. The observation period is from April 2010 until the end of our sample, i.e. 31 August 2011. The Granger causality direction is indicated by the direction of the arrow. The number above the arrow indicates the level of significance of rejection of the null of the Diks and Panchenko test. If no Granger causality is observed this is indicated by word No above the arrow. The bandwidth is $\varepsilon = 1.404357$. See also the notes for Table 4.

Source: Own calculations.

The findings of the paper also have important implications for the financial investors from the perspective of international portfolio management. A well accepted financial axiom states that international diversification reduces risk of a portfolio of financial investments. Therefore, spillovers between sovereign bond markets would diminish the advantage of international diversification. Investors that wish to maximize the risk-return profile of their internationally diversified portfolio should readjust their portfolio according to changes in return dynamics dependence of the portfolio constitutes. The portfolio diversification benefits in the second sub-period increased, however investors who entered the ″periphery″ sovereign bond markets at the start of the turmoil encountered capital losses as the required yields on ″periphery″ sovereign bonds increased.

Conclusion

In this paper we have studied nonlinear Granger causal relationships (spillovers) between sovereign bond markets of six Eurozone markets (namely France, Ireland, Italy, Germany, Portugal, and Spain). Whereas the existent studies study linear interdependence between sovereign bond markets, we applied a novel nonparametric nonlinear Granger causal test of Diks and Panchenko (2006) that is robust to weakness of other existent nonlinear Granger causality tests. The test is applied on the sovereign bond yield dynamics (i.e. yield changes) time series for the time period from 3 January 2000 – 31 August 2011. We also tested for ″pure″ spillovers between

sovereign bond yield dynamics, i.e. the spillovers after controlling for common and regional factors that impact the sovereign bond yield changes of all countries simultaneously.

We manage to show that strong bi-directional Granger causality existed between the investigated sovereign bond markets regardless whether the regional and world factors were controlled for. To verify if the nature of spillovers has changed after the start of the euro are sovereign debt crisis, we tested for the nonlinear spillovers separately for the period before the start of euro area sovereign debt crisis (period from the start of 2000 until the end March 2010) and separately for the period after the start of the euro area sovereign debt crisis (period from the start of April 2010 until the end of our sample, i.e. 31 August 2011). We found that the sovereign bond markets were fairly connected as for all but one pair (namely, France-Ireland) we fond significant nonlinear Granger causality. During the euro area sovereign debt crisis the interdependence between the markets reduced. Nonlinear spillovers running from Germany and France to the ″periphery″ euro area countries could no more be detected thus implying a sort of ″decoupling″ of dynamics in the ″core″ from the ″periphery″ euro area sovereign bond markets.

The findings of this study have important implications for the policymakers as they show that shocks spill-over quickly across the sovereign bond markets. As the shocks in sovereign bond markets can swiftly spill-over from one to another country, economic policy that reassures confidence of investors in sovereign debt market is necessary in case of negative spillovers. The results of this study have important implications also for investors in the investigated sovereign bond markets. The portfolio diversification benefits after the sovereign debt crisis in euro area started increased, however investors who entered the ″periphery″ sovereign bond markets.at the start of the turmoil encountered capital losses from their investments.

While we managed to show that the nonlinear Granger causality between the sovereign bond markets of euro area exists and that the nature of spillovers between sovereign bond markets may change through time, there are several possibilities to complement our research. There are certain other methodologies that would provide additional information on the interdependencies between the sovereign bond markets. For instance, asymmetric GARCH method could be used to analyze how the nature of interdependence changes in the periods of rising and decreasing yields. Furthermore, copula GARCH modelling could be used that also allows nonlinear modelling of dependence between sovereign bond markets. Wavelet method is another possible method that can be applied not just to analyze whether the dependence between markets changing through time, but also whether it is scale dependent.

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