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Foods, Fuels or Finances: Which Prices Matter for Biofuels?

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Foods, Fuels or Finances: Which Prices Matter for Biofuels?

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Abstract:

We examine co-movements between biofuels (ethanol and biodiesel) and a wide range of commodities and assets in the USA, Europe, and Brazil. The main contributions are twofold. First, we analyze a unique dataset of 32 commodities and relevant assets (between 2003 and 2015) which is unprecedented in the biofuels literature. And second, we combine the minimum spanning trees correlation filtration to detect the most important connections of the broad analyzed system with continuous wavelet analysis which allows for studying dynamic connections between biofuels and relevant commodities and assets and their frequency characteristics as well. We confirm that for the Brazilian and US ethanol, their respective feedstock commodities lead the prices of biofuels, and not vice versa. This dynamics remains qualitatively unchanged when controlling for the influence of crude oil prices. As opposed to the Brazilian and US ethanol, European biodiesel exhibits only moderate ties to its production factors.

Keywords: biofuels, prices, minimum spanning tree, wavelet coherence

JEL: C22, C38, Q16, Q42

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1 Introduction

Biofuels have become a solid part of the climate change as well as the food and energy security discussion leading to crucial policies and political decisions worldwide. The current social and economic research has moved from the early engineering-based analyses of transformation ratios of the biofuels feedstock food commodities and the greenhouse gas emission comparisons (Rajagopal & Zilberman 2007) towards analyses of the place of biofuels in the broad system of various commodities and assets with a special focus on the interactions among them (Cha & Bae 2011; Janda *et al.* 2012; Zilberman *et al.* 2013; Serra & Zilberman 2013; Kristoufek *et al.* 2014).

Among various studies of connections between biofuels (mostly ethanol and biodiesel) and related commodities, the analyses usually suffer from an arbitrarily selected set of impulse variables, which might lead to spurious results caused by the aforementioned selection bias. However, as argued by Savaşçin (2011), Serra & Zilberman (2013) and Rezitis (2015), it is possible and likely that the interconnections between biofuels and other-than-feedstock commodities as well as other economic and financial variables may play an important role as well. Even though there are several studies investigating the relationship between specific exchange rates and the system including oil and agricultural commodities (Nazlioglu & Soytaş 2011a;b; Rezitis 2015), the inclusion of stock indices, bond rates and interbank interest rates is rare. Also the existing studies considering financial variables (exchange rates) did not explicitly include biofuels (ethanol or biodiesel) into the analysed system. An important motivation behind utilizing a wide portfolio of assets (regardless the theoretical existence or non-existence of links and connections among them) is the empirically found growing correlation among all types of assets with different fundamentals, which has become even more pronounced after the financial crises of the past decade, mainly due to financialization of commodities (Tang & Xiong 2012; Büyüksahin & Robe 2014; Avdulaj & Barunik 2015). Investigating the dynamics and evolution of connections among biofuels and a wide range of other assets (both related and unrelated to biofuels) is thus novel and it is one of our main contributions.

Even though such a broad approach to studying relationships between relevant factors is very appealing, it brings at least two serious methodological complications. First and likely foremost, the data availability is already an issue for studying even quite narrow datasets. For a wide system of commodities, assets and other economic and financial variables, the complication could become even more severe. And second, the final model can easily become over-specified if too many variables are included. Here, we provide a coherent study of a wide portfolio of biofuels-related assets as well as other important variables suggested in the literature (Serra & Zilberman 2013; Rezitis 2015). To touch the first of the above mentioned issues, we have collected a wide system of 32 biofuels-related commodities and assets at weekly frequency between 2003 and 2015, which is significantly large and more comprehensive set of variables as compared to the previous biofuels literature. For the latter issue, we implement a two-step approach to the problem. We initially identify the most relevant connections in the studied system and then we focus only on these to uncover the specifics of the relationship between biofuels (namely the US and Brazilian ethanol, and German biodiesel) and these relevant factors.

In the first step of our approach, we examine the whole portfolio of assets suggested in the literature (Serra & Zilberman 2013) as potentially related to biofuels and we apply

the method of minimal spanning trees (MST), introduced to the biofuels literature by Kristoufek *et al.* (2012), to identify the most relevant connections and co-movements between the factors during three major periods of the recent biofuels developments. We separately consider the 2003-2008 period leading to the global food crisis, the 2008-2011 period between the 2008 and 2011 global food prices peaks, and finally the 2011-2015 aftermath of the global food price crises. Our MST analysis supports the intuitive result that for each biofuel, the closest price co-movement exists between its major feedstock and the particular biofuel. We also show that the financial factors suggested in the literature on co-movement between oil and exchange rates (Reboredo 2012b; Reboredo & Rivera-Castro 2013; Reboredo *et al.* 2014), oil and stock market (Bastianin & Manera 2015; Jammazi & Reboredo 2015; Reboredo & Rivera-Castro 2014), and oil, agricultural commodities and exchange rate (Rezitis 2015) do not significantly interact with biofuels prices.

While the MST approach easily allows for considering co-movements among essentially unlimited number of possible factors, it does not provide information on the direction of these co-movements. Therefore, as the second step of our analysis, we take the most relevant pairs identified by MST and we conduct an in-depth investigation of their mutual co-movements using an extended wavelet coherence framework introduced to the biofuels literature by Vacha *et al.* (2013). This way, we are able to comment on the directionality of the relationship as well as its scale effect and its evolution in time. The results bring a substantial contribution to the important policy debate on impact of biofuels on food security (Searchinger *et al.* 2015).

Our paper is an integral part of the wide literature on biofuels related price transmission. The most comprehensive recent treatment and literature overview of this topic is provided in the book by de Gorter *et al.* (2015) which is complemented by a series of related papers (Drabik *et al.* 2015; 2014a;b; Rajcaniova *et al.* 2013; de Gorter *et al.* 2013) focused mainly on biofuels policies and prices. While an introduction to the conceptual issues of modeling the impact of biofuels on commodity food prices is outlined by Zilberman *et al.* (2013), the technical issues and extensions to other related prices, including the environmental impacts, are covered by more recent papers by Jianxu *et al.* (2015), Piroli *et al.* (2015), Bastianin *et al.* (2014a), Bastianin *et al.* (2014b) and Hochman *et al.* (2014).

2 Methodology

2.1 Minimal Spanning Trees

The minimal spanning trees (MST) provide a metrics to measure the interconnections within a group of commodities and assets. The construction of MST builds on a sample pairwise Pearson correlation coefficient $\hat{\rho}_{ij}$ between assets i and j . Following Mantegna (1999), the correlation coefficients are transformed into a distance measure

$$d_{ij} = \sqrt{2(1 - \hat{\rho}_{ij})}. \quad (1)$$

Unlike $\hat{\rho}_{ij}$, the distance measure d_{ij} is a true distance measure fulfilling the axioms of Euclidean metrics and it ranges between 0 and 2. Specifically, the corner cases of the cor-

relation coefficient can be translated into the distance measure language in the following manner:

$$d_{ij} = \begin{cases} 0 & \text{perfect positive correlation;} \\ \sqrt{2} & \text{no correlation;} \\ 2 & \text{perfect negative correlation.} \end{cases}$$

Each correlation coefficient $\hat{\rho}_{ij}$ is transformed into a distance measure d_{ij} so that the correlation matrix \mathbb{C} can be transformed into a distance matrix \mathbb{D} ¹:

$$\mathbb{C} = \begin{pmatrix} \hat{\rho}_{11} & \hat{\rho}_{12} & \dots & \hat{\rho}_{1n} \\ \hat{\rho}_{21} & \hat{\rho}_{22} & \dots & \hat{\rho}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\rho}_{n1} & \hat{\rho}_{n2} & \dots & \hat{\rho}_{nn} \end{pmatrix} \Rightarrow \mathbb{D} = \begin{pmatrix} 0 & d_{12} & \dots & d_{1n} \\ d_{21} & 0 & \dots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \dots & 0 \end{pmatrix} \quad (2)$$

Using the values of \mathbb{D} , we find the most important connections within a group of commodities and assets according to the MST concept using the Kruskal's algorithm (Kruskal 1956). The technical details of forming the minimal spanning tree with applications to the biofuels network are covered in Kristoufek *et al.* (2012) and the interested reader is thus referred there. In short, the tree of the most important connections of the system are formed by systematically eliminating the weakest links (the longest distances) between nodes (commodities and assets) as long as the tree is not torn between more trees, i.e. as long as it is possible to connect any two nodes using the remaining links. The resulting tree is best understood from its graphical representation, which is done in the Results section in detail. Note that the elimination of the less relevant connections leads to a decreased number of links and thus also a lowered risk of over-specification. Namely, the number of links decreases from $k(k-1)/2$ for the correlation matrix to $k-1$ for the final minimal spanning tree, where k is the number of variables. Such correlation matrix filtration has proved its worth in various applications across disciplines (Song *et al.* 2012; Gramatica *et al.* 2014; Musmeci *et al.* 2015).

A potential issue of the MST analysis lays in a possible link instability, i.e. whether the detected relevant link is in fact relevant or is present due to statistical noise. This is usually an issue for systems with overall weak connections. In order to assess stability (importance) of individual links, we employ the bootstrapping technique proposed by Tumminello *et al.* (2007). In the procedure, the time series are resampled with repetition from the original series while the variable of resampling is time, i.e. we resample from the time index and reconstruct the analyzed series according to the new time structure. This way, the pairwise correlation core is not distorted. The MST procedure is then applied on the bootstrapped series and the relevant links are recorded. This is repeated 1000 times. Resulting bootstrap values are reported for each link in form of b_{ij} which is defined as a ratio between the number of occurrences by the total of bootstrapped realizations so

¹Note that the diagonal elements of the distance matrix are equal to zero corresponding to the unit value of $\hat{\rho}_{ii}$.

that $b_{ij} \in [0; 1]^2$. As argued by Tumminello *et al.* (2007) and Tumminello *et al.* (2010), the bootstrapping testing procedure is connected to the link strength but rather weakly so that it in fact provides additional information about the connection between variables. In the empirical application, we set $b_{ji}^* = 0.5$ as a threshold for a stable link³. As stressed by Tumminello *et al.* (2007), the procedure has no strict assumptions about multivariate distribution of the analyzed processes and it implicitly takes into account the time series length.

2.2 Wavelet Coherence

The most important connections in the analyzed system of commodities and assets identified through MST are further investigated in more detail using the wavelet coherence framework, which is a significant generalization of the simple correlation analysis as it allows for examination of the time evolution of the relationship between series as well as its scale structure, i.e. whether the connection are important from different temporal perspectives.

Wavelet analysis decomposes a time series into several components according to their time and scale properties. Generally, a signal (time series) may be composed of individual waves cycling at different speed, i.e. with different frequencies. Individual components of the signal get separated in the frequency domain. A central feature of wavelet analysis is that it captures both time and frequency characteristics, i.e. it decomposes the series in both domains.

A wavelet $\psi_{u,s}(t)$ is a real or complex-valued function given as

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right), \quad (3)$$

with a scale parameter s and a location parameter u . Under certain conditions, in detail discussed by Daubechies (2004), the original series $\{x_t\}$ can be fully reconstructed from its wavelet transform $W_x(u, s)$ defined as

$$W_x(u, s) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{s}} \psi^*\left(\frac{t-u}{s}\right) dt, \quad (4)$$

where $*$ represents a complex conjugate operator preventing an information loss during the transformation. The degree of similarity between the wavelet shape and $\{x_t\}$ is measured by the integral above. Frequently, multivariate economic applications of wavelet analysis use the Morlet wavelet which, as a complex wavelet, enables studying multivariate relationships between series⁴. As an example of different wavelet used in energy economics we may consider Haar a Trouse wavelet (Jammazi & Reboredo 2015).

²Computations associated with the construction of MST are processed in R software. Visualizations are conducted using the `igraph` package.

³Note that setting $b_{ji}^* = 0.5$ is rather arbitrary but we follow Tumminello *et al.* (2007) and Tumminello *et al.* (2010) where links with even $b_{ji} > 0.4$ are considered stable enough. There is no specific ideal threshold that would be agreed on in the topical literature.

⁴The Morlet wavelet is specified as $\psi^M(t) = \frac{1}{\pi^{1/4}} e^{i\omega_0 t} e^{-t^2/2}$ where ω_0 denotes the central frequency of the wavelet. We set $\omega_0 = 6$ as it provides an optimal balance between time and frequency components (Aguar-Conraria *et al.* 2008; Rua 2010; Vacha *et al.* 2013; Vacha & Barunik 2012).

The wavelet framework can be generalized into a bivariate setting which is essential for studying connections between various series. In the bivariate setting, the cross wavelet spectrum is given by

$$W_{xy}(u, s) = W_x(u, s)W_y^*(u, s), \quad (5)$$

where $W_{xy}(u, s)$ stands for the continuous wavelet transform of series $\{x_t\}$ and $W_y^*(u, s)$ marks a complex conjugate of the continuous wavelet transform (Torrence & Compo 1998). As the cross wavelet spectrum is generally complex, the cross wavelet power is given by $|W_{xy}(u, s)|$. It is usually understood to be a measure of local covariance between two series at a given frequency. Nonetheless, we cannot easily assess the strength of the detected co-movement as the cross-wavelet power is not bounded (in the same logic as standard covariance). To overcome such limitation, the squared wavelet coherence is introduced as

$$R_{xy}^2(u, s) = \frac{|S(\frac{1}{s}W_{xy}(u, s))|^2}{S(\frac{1}{s}|W_x(u, s)|^2)S(\frac{1}{s}|W_y(u, s)|^2)}, \quad (6)$$

with S being a smoothing operator (Torrence & Webster 1998). By definition, the value of the squared coherence varies between 0 and 1. Moreover, the squared wavelet coherence corresponds to the usual squared correlation coefficient for specific time and frequency. As the cross-wavelet spectrum translates into the squared coherence, the information about the direction of the relationship is lost. However, this information can be recovered from its phase difference specified as

$$\varphi_{xy}(u, s) = \tan^{-1} \left(\frac{\Im [S(\frac{1}{s}W_{xy}(u, s))]}{\Re [S(\frac{1}{s}W_{xy}(u, s))]} \right), \quad (7)$$

with \Re and \Im representing the real and imaginary part operators, respectively. Furthermore, we test statistical significance of the coherence using the Monte Carlo simulation method. For technical details, please refer to Grinsted *et al.* (2004).

As pointed out by Kristoufek *et al.* (2016), wavelet coherence is limited by the same technical constraint as usual correlation – it may suffer from the omitted variable bias as it does not control for a possible influence of other variables. Thus, we may observe a (seemingly) high coherence between two variables while the observed relationship can in fact be caused by their mutual ties to another variable. To overcome this issue, we follow Kristoufek *et al.* (2016) in using the partial wavelet squared coherence, an analogy of the partial correlation, defined as

$$RP_{y,x_1,x_2}^2 = \frac{|R_{yx_1} - R_{yx_2}R_{yx_1}^*|^2}{(1 - R_{yx_2}^2)^2(1 - R_{x_2x_1}^2)^2}. \quad (8)$$

Partial wavelet coherence evaluates the relationship between $\{y\}$ and $\{x_1\}$ while controlling for the effect of $\{x_2\}$, see Mihanovic *et al.* (2009) for details.

In the same way as for the minimal spanning tree approach, an outcome of the wavelet analysis is best understood from its graphical representation, which is discussed and described in detail in the Results section⁵.

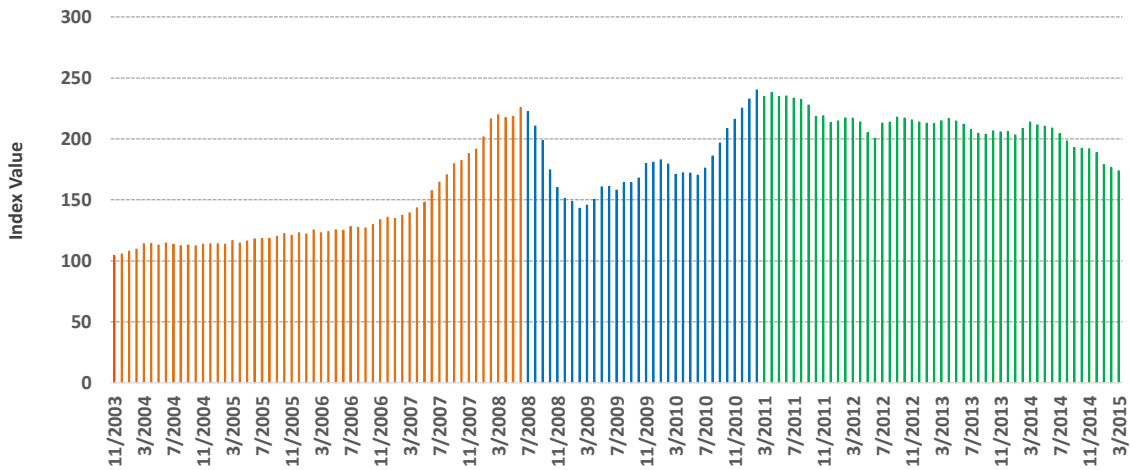
⁵The computational process of wavelet analysis was processed in MATLAB R2014b using packages by Aslak Grinsted and E. K. W. Ng and T. W. Kwok.

3 Data

3.1 Dataset Description

In search for a system of commodities and assets that are related to biofuels, we follow a comprehensive approach. Our dataset is gathered from various sources in order to systematically include representative items of the following asset classes: biofuels (both ethanol fuel and biodiesel), ethanol feedstock, biodiesel feedstock, fossil fuels (including crude oil), food, stock indices, exchange rates, and interest rates. In contrast to previous studies we intend to substantially increase the number of items considered in the analysis. The final count is therefore a portfolio of 32 series ranging between 24 November 2003 and 19 January 2015, i.e. over 11 years, which is unprecedented in the biofuels literature.

Figure 1: Food Price Index



Data Source: Food and Agricultural Organization of the United Nations

Over these 11 years, the commodity markets went through a number of structural changes. Resulting price development exhibits several different patterns. In order to account for various market environments, we split the whole period into three subperiods for the initial minimal spanning tree analysis. As a benchmark for the splitting, we use the Food Price Index⁶ published by the Food and Agriculture Organization of the United Nations (FAO) providing a broader notion about the development of agricultural commodity prices. Figure 1 shows the index development between 11/2003 and 03/2015. One can observe an upward sloping trend culminating in the 2007-2008 world food crisis with the index value peaking in June 2008. Subsequently, the agricultural prices fell bottoming in September 2009 before catching up again for a new food commodity prices rally. The index reached its new peak in February 2011 followed by a stable price decrease.

Having inspected historical behavior of the index, we assign the two aforementioned index peaks to be the breaking points. We thus obtain three subperiods of unequal

⁶The FAO Food Price Index (measured in points) captures the monthly levels of international food prices. It is a weighted average of five commodity group price indices. Weights are represented by average export shares of each group during 2002-2004. (Detailed description together with the underlying data can be found at www.fao.org/worldfoodsituation/foodpricesindex.)

lengths as depicted in Figure 1. The subperiods are as follows:

- Period I: November 24, 2003 - June 30, 2008 with 241 weekly observations.
- Period II: July 7, 2008 - February 28, 2011 with 139 weekly observations.
- Period III: March 7, 2011 - January 19, 2015 with 203 weekly observations.

In the minimal spanning tree analysis, we study three subperiods to distinguish between different development stages of the biofuel industry. Our dividing points exactly correspond to the World Bank terminal points of the two global food crises in 2008 and 2011. As summarized by Cuesta *et al.* (2014), the World Bank developed a methodological approach to identify a situation leading to a potential food crisis.

We follow with a detailed description of the commodities and assets employed. The items are grouped according to their specific type. To ensure a quick orientation in resulting minimum spanning tree objects, individual groups are graphically differentiated by colors.

Biofuels

Since our primary focus is on the first generation biofuels, their inclusion is clearly justified. Although the prices are not volatile enough on daily basis, studied biofuel markets exhibit sufficient liquidity to be analyzed on weekly frequency. In the MST structure, biofuels are colored in green. We consider biodiesel and the US as well as the Brazilian ethanol.

As majority of the world's ethanol is produced in the USA followed by Brazil, we include prices of both the US ethanol and the Brazilian ethanol represented by the New York Harbor Price and Centro de Estudos Avancados em Economica Aplicada (CEPEA) Ethanol Index, respectively. The New York Harbor price is a spot price Free on Board (FOB) quoted in the US cents per gallon. The data was obtained from Bloomberg database under the ticker ETHNNYPR Index. It is a denaturated anhydrous fuel ethanol designed for blending with gasoline as explained by Kristoufek *et al.* (2012). The Brazilian ethanol price is reported by CEPEA for anhydrous fuel ethanol. The data was downloaded from the CEPEA website (cepea.esalq.usp.br).

As opposed to ethanol which leads the biofuels production in the USA and Brazil, biodiesel is primarily produced in Europe. Biodiesel stands for the most important biofuel in the European Union accounting for about 80% of its biofuel used in transportation. Therefore, we searched for suitable data which would represent the price of European biodiesel. At this point, we had to cope with a severe data unavailability. The variety of suitable European biodiesel tickers available from the standard Bloomberg terminal is very limited and many of the time series are too short to be meaningfully employed. We finally solved the issue by including the data from two different sources. Spot price of the German consumer biodiesel (sourced from the Bloomberg terminal as BIOCEUGE ATPU FOL Index) is used for Periods I and II. Period III is then covered by the Dutch biodiesel data gathered and provided by Reuters. Specifically, we employ a price series labeled as FAME 0 FOB ARA Spot. The label corresponds to FOB spot price of Fatty Acid Methyl Ester traded OTC in harbors of Amsterdam, Rotterdam, and Antwerp. Being quoted in USD per metric ton, this type of biodiesel conforms to EN 14214 norm set at 0°C with a maximum water content of 350 ppm.

Ethanol Feedstock

Ethanol is produced from crops that are rich in sugars. Most of the world's ethanol is obtained from corn (in the USA), followed by sugarcane (in Brazil). Other frequent ethanol feedstock include wheat and sugar beets. Still other agricultural commodities may be technically used to produce ethanol, for example cassava, potatoes, cotton or sorghum. In case of the US, we consider the following American commodities: corn, wheat, sugarcane, and sugar beets as they account for a vast majority of the American ethanol production. The data represents USD prices and come from Bloomberg. For Brazil, we include the price of Brazilian sugar as a proxy for local sugarcane price. The data is provided by CEPEA. In the MST structure, the ethanol feedstock is represented by red color.

Biodiesel Feedstock

As mentioned above, biodiesel represents the primary European biofuel. The EU is the world's biggest producer of biodiesel. Nonetheless, the global volume of produced biodiesel is substantially smaller than the world's ethanol production. Technically, biodiesel may be produced from a variety of vegetable oils and biolipids. However, rapeseed and soybean oils are the most frequent feedstock commodities. In addition to rapeseed and soybean oils, we also include sunflower and palm oil in the dataset. Due to data unavailability, sunflower seeds (Bloomberg ticker SU1) are used instead of sunflower oil. The data was obtained from Bloomberg. In MST, biodiesel feedstock is visualized in pink color.

Fossil Fuels

Biofuels represent an alternative to traditional fossil fuels as their substitutes. Our dataset thus contains crude oil price as it is not only the main input into the other fuels' production but it also stands for a very actively traded commodity. As our focus is on ethanol and biodiesel, we include such fossil fuels that compete with our biofuels from a local perspective. Thus, German diesel and German gasoline are considered because of their competitive relation to the European biodiesel. Similarly, we include US gasoline and US diesel as well as Brazilian gasoline and Brazilian diesel to serve as a counter party for the US and Brazilian ethanol, respectively. The price of (Brent) crude oil comes from Bloomberg. Retail prices of both US/German gasoline and US/German diesel were obtained from the website of the US Energy Information Administration (EIA). The prices are quoted in USD per gallon excluding taxes. For the Brazilian fuel prices, we referred to the National Agency of Petroleum, Natural Gas and Biofuels – Agencia Nacional do Petroleo, Gas Natural e Biocombustiveis – ANP (www.anp.gov.br). We employ the weekly weighted average consumer prices for gasoline and diesel which we previously converted to US dollar prices per gallon. In the MST structure, fossil fuels are shown in gray color.

Food

In addition to agricultural commodities that are used as biofuel feedstock both in Americas and in Europe, we cover selected purely food commodities as well. Our dataset

contains coffee, cocoa, rice, and oranges. These commodities cannot be used to produce biofuels, however all of them are frequently traded agricultural products that compete with biofuel feedstock over the cultivated land. Food commodity prices come from Bloomberg and in the MST analysis, these are visualized in purple.

A comprehensive overview of non-energy commodities by Savaşçın (2011) serves as a good inspiration when searching for possible other factors which may influence the dynamics of biofuels prices. As proposed by Serra & Zilberman (2013), an analysis investigating potential price links between biofuels and other commodities should not omit external factors that might affect price links within the food–energy system. These factors include price development of stocks or futures, policy regulations, and macroeconomic conditions, e.g. exchange rates or interest rates. Similarly, Kristoufek *et al.* (2012) recommend to extend the MST taxonomy analysis not only in terms of goods or commodities but also by inclusion of assets such as stocks, exchange rates or interest rates. These recommendations have motivated our decision to increase the complexity of our price system by the following three groups.

Stock Indices

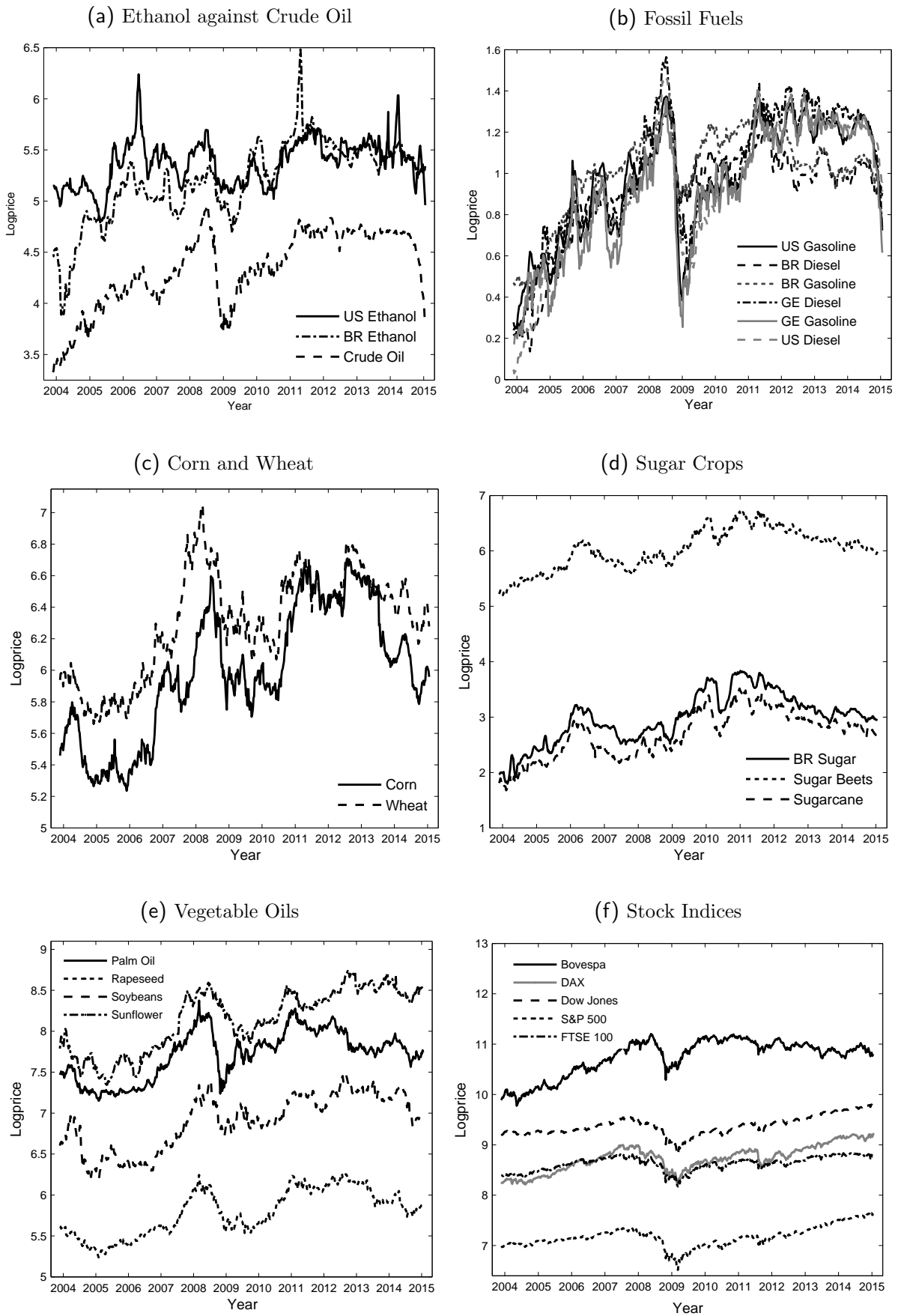
A national stock index may serve as a good proxy of GDP reflecting the atmosphere in a particular market at a given point in time. The choice of stock indices is suitable because usual GDP data is not available at a weekly frequency. We cover the major indices that geographically correspond to the markets of our interest. Namely, we include Dow Jones Industrial Average and S&P 500 to represent the US stock market, Financial Times Stock Exchange 100 Index (FTSE 100) and Deutscher Aktienindex (DAX) to account for the British and German stock markets, respectively. Moreover, due to our interest in Brazilian ethanol, we also include the Brazilian Bolsa de Valores do Estado de Sao Paulo (Bovespa) index. Market data for all the indices was obtained from the Bloomberg platform. The group of stock indices is differentiated by orange color in the MST analysis.

Interest Rates

From a general perspective, interest rates reflect the nature of macroeconomic conditions. In our case though, there arises an issue with data frequency since a lot of key interest rates are not set on a weekly basis. However, we choose two interest rates that are set daily. The US Federal funds rate represents the base interest rate of the US Federal Reserve. Fed funds is the interest rate a bank uses for the overnight lending to another bank and it is set on an open market. The data was downloaded from the Fed’s website. We consider federal funds rate available under www.federalreserve.gov.

The London Interbank Offered Rate (LIBOR) – former BBA LIBOR – is now quoted daily by the Intercontinental Exchange. It serves as a global benchmark for short term interest rates. Out of the variety of currencies and borrowing periods we take 3 months USD LIBOR as it is supposed to be the most liquid one. The data was obtained from the ECONSTATS’s website (www.econstats.com). Interest rates are visualized in blue.

Figure 2: Selected Logarithmic Prices



Exchange Rates

Our analysis focuses on three geographical markets where a majority of the world’s bio-fuels are produced – the USA, the EU, and Brazil. For this reason, we consider the USD/EUR and USD/BRL exchange rates. As stressed by Algieri (2014), international food (as well as other commodity) prices are denominated in the US dollars. However, since consumers pay for commodities in their local currency, changes in the USD exchange rate affect supply and demand which translates into price changes. We may observe that a strengthening USD means falling commodity prices. Historical data on USD/EUR was gathered from the European Central Bank (sdw.ecb.europa.eu). The USD/BRL rate was obtained from the US Federal Reserve (www.federalreserve.gov). In the MST charts, the exchange rates are depicted in yellow color.

3.2 Development of Prices

For the sake of simplicity, the term price is used also in a natural reference to stock index values, interest rates or exchange rates throughout this paper. Figure 2 presents the development of the studied weekly logarithmic USD prices. In the price chart (a), we observe that both the US and Brazilian ethanols follow a similar path. To ensure legibility of the figure, crude oil price is plotted together with biofuels instead of fossil fuels. All fossil fuels in (b) exhibit a strong co-movement. However, both Brazilian fuels still stand a bit aside showing a relatively milder price development during the recession. Ethanol feedstock prices are plotted in two separate graphs. In (c), corn exhibits a very strong co-movement with wheat. Similarly, there is a natural similarity between price movements of sugar beets and sugarcane in (d). Vegetable oils which are feedstock for biodiesel all follow a similar path at different price levels (e). The development of stock indices is captured in chart (f).

For the purpose of our analysis, we convert our price series P_t into logarithmic returns r_t defined as

$$r_t = \log(P_t) - \log(P_{t-1}) = \log\left(\frac{P_t}{P_{t-1}}\right). \quad (9)$$

The use of logarithmic returns is suitable due to their symmetry as discussed by Hudson & Gregoriou (2010). We also benefit from an earlier analysis by Kristoufek *et al.* (2012) who apply the same transformation. Thus, we ensure comparability of results. Moreover, the use of logarithmic returns instead of simple prices is beneficial for a technical reason. As will be further explained below, when transforming prices into returns, we technically obtain first differences. This fact turns out to be crucial for the discussion of time series stationarity.

Our analysis stands on a construction of MST using a distance metric. Strictly speaking, our distance metric d_{ij} is a transformed correlation coefficient. As we compute correlations, stationarity plays a vital role. Thus, we need to check for stationarity of our time series. For this purpose, we will employ the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller 1979) and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Kwiatkowski *et al.* 1992). Both stationarity tests performed on the series of logarithmic returns (582 observations) yield straight and satisfactory results. All analyzed series turn out to be stationary under both ADF and KPSS tests. Non-stationarity is strongly rejected without

any exception. Tests' results can be inspected in Table 1.

4 Results

4.1 Minimal Spanning Trees

This section builds and visualizes an interconnected system of biofuel-related commodities and assets. To our knowledge, we are the first to construct a similarly complex system of commodities and assets that are associated with the global production of biofuels. The inclusion of purely food commodities was inspired by a recommendation of Serra & Zilberman (2013). We also took an advice from Kristoufek *et al.* (2012) who had proposed considering relevant financial series such as exchange rates, interest rates or stocks indices.

4.1.1 Period I, 2003 – 2008

In order to explain a practical use of the MST methodology, we start with a description of how a particular MST comes to existence. For each period, we employ logarithmic returns on weekly frequency.

When constructing a minimal spanning tree, we are interested in visualizing the most important connections among the vertices. The importance of an edge is determined by the strength of correlation between the two given vertices. Simple correlation is transformed into the distance measure, d_{ij} – the stronger the correlation, the shorter the edge. Actual values of realized distances d_{ij} are indicated by blue bold numbers attached to the edges.

Apart from distances between the vertices, we also test the stability of the links using the bootstrap method. We inspect how many times out of a thousand bootstrapped realizations a particular connection appeared in the tree. A robust link being present more than 500 times is marked by a double asterisk sign. On the contrary, single asterisk designates a rather unstable link.

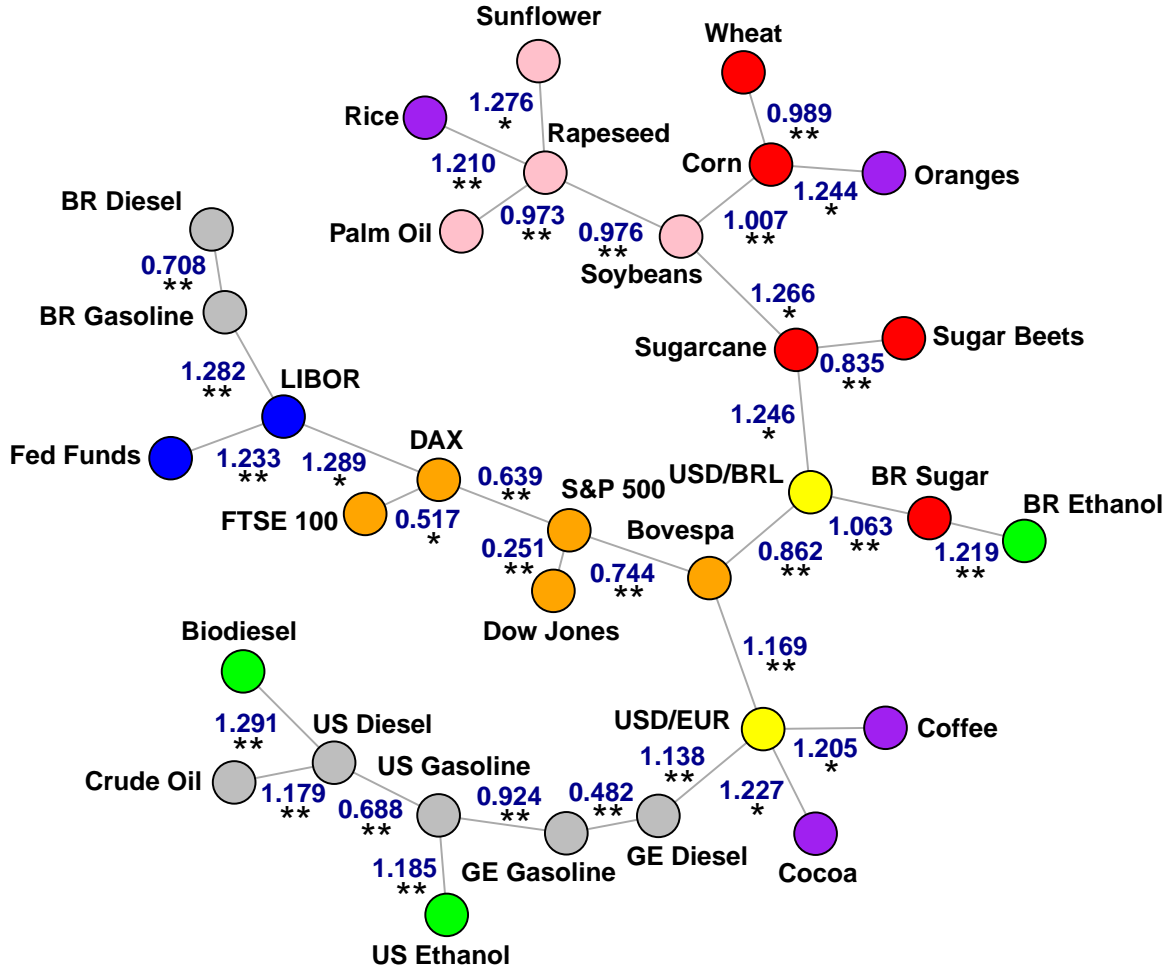
Exploring the weekly logarithmic returns, we found the shortest edge ($d_{ij} = 0.251$) between the US stock indices. Hence, Dow Jones and S&P 500 create the first pair, a nascent MST. The second shortest link ($d_{ij} = 0.482$) was identified between German gasoline and German diesel. The third strongest correlation exists between the European stock indices, FTSE 100 and DAX, ($d_{ij} = 0.517$). At this point, our MST consists of three separate pairs: Dow Jones–S&P 500, GE gasoline–GE diesel, and FTSE 100–DAX. The next shortest distance ($d_{ij} = 0.639$) is then found between DAX and S&P 500 which are both already present in the MST. By matching these vertices, we create a quadruple through connecting the two pairs. The fifth highest correlation exists between US gasoline and US diesel, ($d_{ij} = 0.688$). We add a new separate pair since neither of these fuels has yet been present in the MST. The connection between Brazilian gasoline and Brazilian diesel ($d_{ij} = 0.708$) creates a separate fuel pair. The next shortest edge ($d_{ij} = 0.744$) connects Bovespa to the S&P 500 on the already existing quadruple of the remaining stock indices.

Our MST now consists of a quintuplet of stock indices and three separate (gasoline–diesel) retail fuel pairs. Further steps add a separate sugarcane–sugar beets pair and then

Table 1: Stationarity Tests – Log Returns

	ADF	p-value	KPSS	p-value
Biodiesel	-8.2985	< 0.01	0.1045	> 0.1
US Ethanol	-9.1553	< 0.01	0.0918	> 0.1
BR Ethanol	-8.2474	< 0.01	0.0797	> 0.1
Crude Oil	-5.6530	< 0.01	0.3120	> 0.1
Corn	-6.5972	< 0.01	0.1209	> 0.1
Wheat	-8.0847	< 0.01	0.1036	> 0.1
Sugarcane	-7.4650	< 0.01	0.1691	> 0.1
Sugar Beets	-7.6338	< 0.01	0.2776	> 0.1
Soybeans	-6.7541	< 0.01	0.0845	> 0.1
Sunflower	-7.5821	< 0.01	0.0586	> 0.1
Rapeseed	-6.9994	< 0.01	0.0935	> 0.1
Palm Oil	-6.7438	< 0.01	0.0682	> 0.1
US Gasoline	-7.2226	< 0.01	0.1795	> 0.1
US Diesel	-6.3976	< 0.01	0.2315	> 0.1
DE Gasoline	-6.8158	< 0.01	0.1998	> 0.1
DE Diesel	-6.3632	< 0.01	0.2932	> 0.1
BR Gasoline	-7.0856	< 0.01	0.1641	> 0.1
BR Diesel	-7.3788	< 0.01	0.2072	> 0.1
Coffee	-7.5110	< 0.01	0.1472	> 0.1
Cocoa	-9.0287	< 0.01	0.0636	> 0.1
Rice	-7.3896	< 0.01	0.1202	> 0.1
Oranges	-6.2106	< 0.01	0.2487	> 0.1
Dow Jones	-7.8402	< 0.01	0.1297	> 0.1
S&P 500	-7.5160	< 0.01	0.1452	> 0.1
FTSE 100	-8.2013	< 0.01	0.0774	> 0.1
DAX	-8.2896	< 0.01	0.0791	> 0.1
Bovespa	-7.8316	< 0.01	0.2887	> 0.1
Fed Funds	-7.0904	< 0.01	0.1874	> 0.1
Libor	-5.3280	< 0.01	0.2855	> 0.1
USD/EUR	-8.3592	< 0.01	0.1674	> 0.1
USD/BRL	-6.8069	< 0.01	0.3493	> 0.1

Figure 3: Minimal spanning tree, Period I



Note: * if Bootstrap Value < 0.5, ** otherwise, Edge Lengths in bold

connect USD/BRL exchange rate to the Bovespa index. Each time, before a potential new edge is constructed, we need to make sure it will not create an undesirable loop in the MST. Next steps form a fuel quadruple by linking the US and German gasolines ($d_{ij} = 0.924$), before establishing the first vegetable oil pair, rapeseed–palm oil ($d_{ij} = 0.973$). Following this logic, we eventually obtain a complete MST as shown in Figure 3.

Inspecting Figure 3, we observe the visualized characteristics of our experimental network. A core of the MST is formed by a compact group of the stock indices. It follows from the interconnected nature of stock markets that these indices are strongly correlated with stable mutual links. We see that not only stock indices but also a number of other items gather according to their type. In broader terms, there seems to be a group of agricultural commodities — a food branch — and a fuel branch of the MST at the opposite sides of the network. A cluster of the vegetable oils together with the ethanol feedstock commodities constitute the food part of the tree. On the other hand, the fossil fuels and biofuels form the fuel branch. While no other biofuel is connected to its

feedstock, Brazilian ethanol makes a notable exception. Its robust link to Brazilian sugar is evident already during the first studied period. The US ethanol and even biodiesel have stable links to their US fossil substitutes and crude oil.

As opposed to the exchange rates which bridge the stock market cluster with fuel and food parts, interest rates do not seem to interact a lot. Brazilian retail fuels are not integrated into the fuel branch, they stand at the edge of the network being only linked to LIBOR. The isolated position of the Brazilian fossil fuels is implied by a specific setting of the national fuel market in Brazil (Khanna *et al.* 2016). Due to a decisive influence of Petrobras on local fuel prices, Brazilian fossil fuels do not necessarily follow the global markets' development⁷. As we will see during the whole studied period, they do not usually integrate into the fossil fuel cluster. We should not forget about the four purely food commodities which cannot be used to produce biofuels. These items do not form any cluster and are only individually connected to different nodes of the network.

4.1.2 Period II, 2008 – 2011

Our first period covered the era of rising food prices and an increasing global significance of biofuels preceding the first world food crisis covered by our sample. We now continue investigating our network's development in a changed market environment. After several years of accelerating agricultural and energy prices, these slumped quickly during the second half of 2008 hand in hand with the global economic crisis. After the bottom was reached in 2009, both energy and agricultural prices started a new rally up to a new peak in February 2011. During this period, we expect to see signs of an established biofuel production not only in Brazil but also in the US and Europe. Figure 4 delivers a minimal spanning tree for this period. Compared to the previous one, the US ethanol moved to the food branch, connecting to corn. The US ethanol–corn link is relatively short ($d_{ij} = 0.930$) and stable. It reflects an important connection between the main US biofuel and its primary feedstock. In the similar manner, biodiesel gets closer to the vegetable oils cluster and the Brazilian ethanol remains close to the Brazilian sugar and the USD/BRL exchange rate.

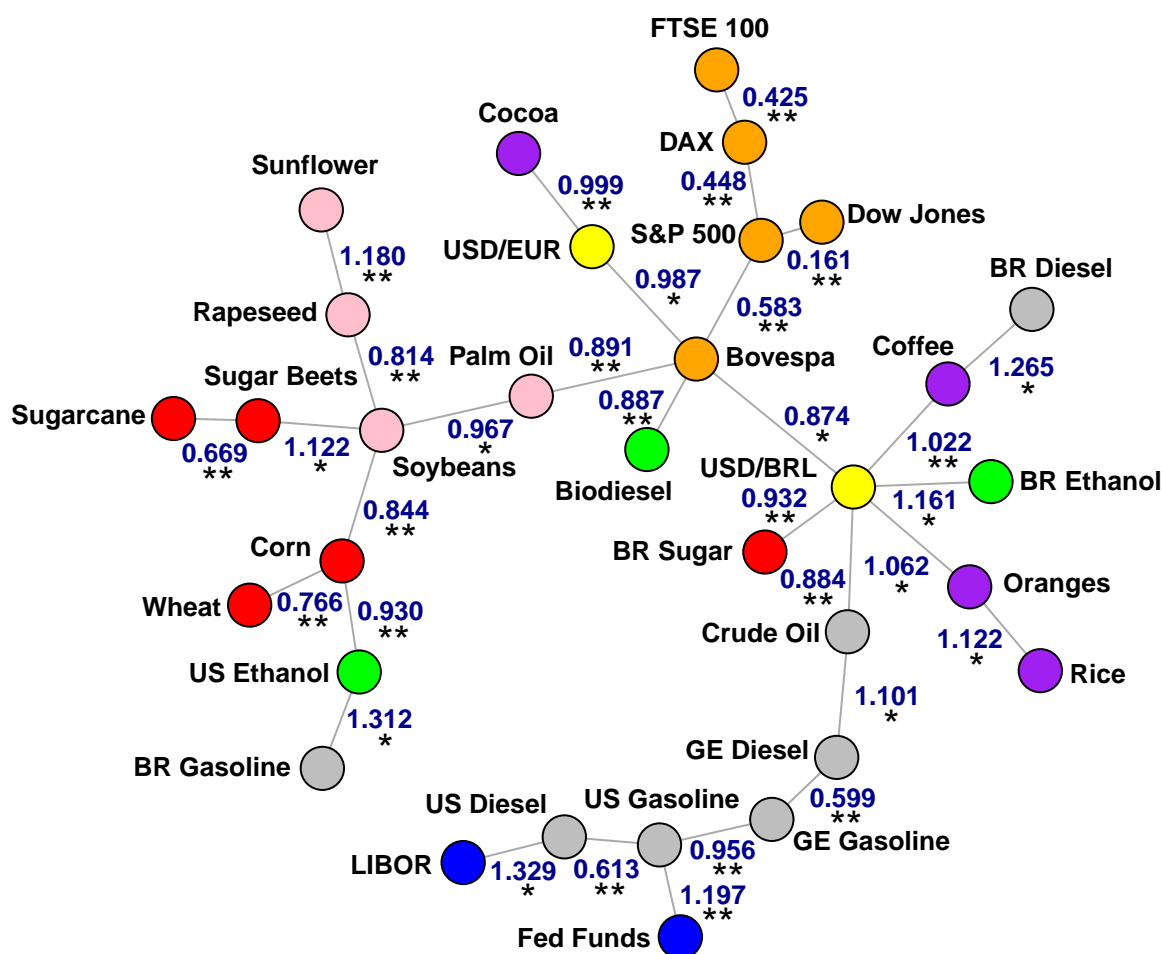
4.1.3 Period III, 2011 – 2015

During the last studied period, the values of FAO Food Price Index (Figure 1) experienced a gradual slowdown continuing until and including January 2015. Considered food and energy prices went through a volatile season during which they approached considerably lower values. At the same time, stock indices grew reaching new all-time highs.

Inspecting the minimal spanning tree in Figure 5, we may draw a clear line separating the fuel from the food branch with the stock indices just in between. Now the visual difference between fossil fuels and agricultural commodities becomes obvious. Exceptionally, both Brazilian fossil fuels get integrated into the fuel cluster. In accordance with the previous findings, the biofuels stay attached to their respective feedstock clusters; however, their mutual links are rather weak. There exist very stable interconnections between palm oil, rapeseed, and soybeans with biodiesel being attached to both sunflower

⁷Petroleo Brasileiro S.A is the Brazilian largest energy corporation with a multinational presence. A share of up to 64% is directly or indirectly controlled by the government.

Figure 4: Minimal spanning tree, Period II



Note: * if Bootstrap Value < 0.5, ** otherwise, Edge Lengths in bold

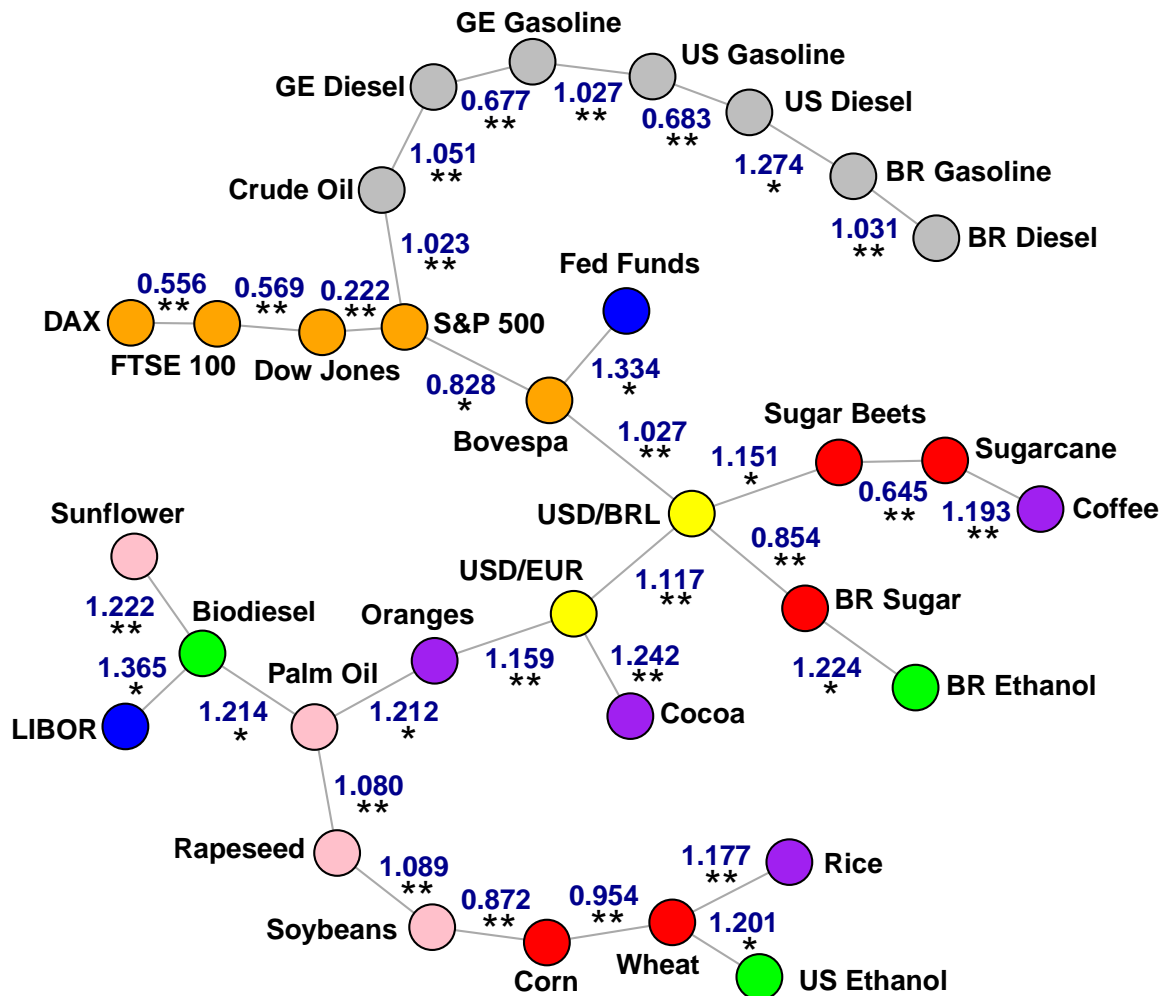
and palm oil.

4.2 Wavelet Analysis

The minimal spanning tree analysis in the previous sections has shown that there is quite noticeable dynamics of the evolution of the MST structure over time. Given the static nature of each MST structure depending on the chosen time window for that particular MST, there is a clear advantage in using continuous wavelet framework capturing the co-movement among the prices of chosen commodities at each time point and at different scales (frequencies) without a need to specify any particular time window or choosing a particular fixed frequency. Having identified several important links between biofuels and their feedstock, we approach these pair connections separately.

Standard correlation coefficient is static and is characteristic to the time dimension only. Wavelet analysis basically adds the frequency dimension into the analysis and makes

Figure 5: MST, Period III



Note: * if Bootstrap Value < 0.5, ** otherwise, Edge Lengths in bold

it dynamic. Therefore, wavelet framework allows for exploring the correlation relationship in both time and frequency domains. The output for each studied biofuel–feedstock pair is presented in form of two charts. While the horizontal axes show time (in years), there is also the scale (in days) on the vertical axes. Coherence is indicated by color according to a spectrum shown at the right edge. Pale colored corner areas are not of reliable interpretation. They result from artificially adding zeros to the beginning and to the end of analyzed series compensating for wavelet lengths. A central bright colored area delivers reliable results. Furthermore, the regions with statistically significant coherence are bounded with a thick black curve.

In the left panel, we present the squared wavelet coherence between biofuel and a given feedstock commodity. Since there is no negative wavelet coherence, phase difference between the series is indicated by directed arrows. Simply put, the arrows show in what direction the relationship is. Rightward pointing arrows mean that biofuel is positively

correlated with that particular feedstock while leftward pointing arrows indicate a negative relationship. If the arrows point straight down, biofuel leads the price of feedstock by $\pi/2$. On the contrary, the upward pointing arrows imply that price of biofuel is led by feedstock.

In the right panel, we present the partial wavelet squared coherence. In the food–fuel system, crude oil plays a role of an important price driver affecting both fuel and food part of the commodity system. To some extent, food, fuel, and biofuel prices can all depend on the crude oil price. Therefore, the wavelet coherence output (left panel) is supplemented by the partial wavelet coherence charts (right panel) where crude oil is controlled for. The increase of the price co-movement between oil and food commodities with the onset of the global food crises is shown by Reboredo (2012a), Rajcaniova & Pokrivcak (2011) and Pokrivcak & Rajcaniova (2011).

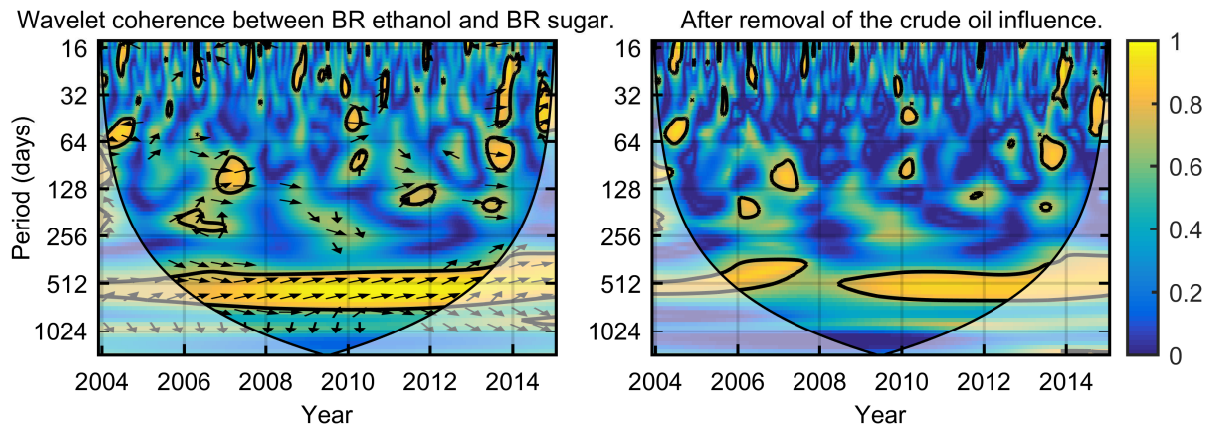
4.2.1 Brazilian Ethanol

In the context of global biofuel production, Brazil represents a unique scenario. The Brazilian ethanol is produced from sugarcane. Intuitively, its price is supposed to be related to the price of feedstock. As documented by our previous MST analyses, the Brazilian ethanol price is directly linked to the price of Brazilian sugar. Moreover, their connection seems to be relatively strong and stable, since it appeared in majority of the constructed MSTs. Hence, we are especially keen on exploring Brazilian ethanol (BR ethanol) correlation with local sugar (BR sugar) price in more detail.

The left panel of Figure 6 shows a strong relationship apparent for scales approximately between 500 and 700 days, i.e. roughly between 1.5 and 2 years. Thus, we observe a long term relationship between the BR ethanol and BR sugar that is remarkably stable in time. Apart from this main relationship, we identify only several minor coherence islands associated with relatively quick price interactions in the short term. These could easily be due to statistical noise. The phase arrows in the main significant region point to the right and upwards indicating a positive correlation between the prices of ethanol and sugar with sugar leading the price of ethanol.

The right panel of Figure 6 delivers the output of the partial wavelet coherence when the influence of crude oil has been controlled for. Apparently, crude oil consumed only a small portion of the overall correlation. The stable long-term relationship between the Brazilian sugar and ethanol reported in the left panel is distracted for a short period around 2008 after controlling for the crude oil influence. This time period overlaps with historical heights of crude oil prices when a barrel of crude oil rocketed over \$140 in July 2008. This suggests that crude oil has a stronger effect on ethanol when the prices are high. Such claim is well in hand with the results of Chang & Su (2010), Cha & Bae (2011), Nazlioglu (2011), Timilsina *et al.* (2011) and Nazlioglu *et al.* (2013) who detect different non-linear relationships between crude oil, biofuels, and their feedstocks, specifically with respect to high crude oil prices. Our results do not only support the findings of the previously mentioned studies but also describe the dynamics in more detail. Specifically, only the long-term relationship is torn for the crude oil highs but there are no emerging short-term correlations as a result of the crude oil spikes. The relationship between the Brazilian ethanol and sugar thus remains remarkably stable in time, which has been reported in the MST analysis as the connection between the Brazilian sugar

Figure 6: Wavelet coherence: Brazilian ethanol versus feedstock



Wavelet squared coherence (*left*) and partial wavelet coherence (*right*)
 Coherence color spectrum shown at the right edge. Thick black curve marks
 significant regions. Phase differences are indicated by the directed arrows.

and ethanol having been found strong and reliable during all three analyzed periods.

For decades now, Brazil represents an example of an active biofuel economy. During more than forty years history, Brazilian ethanol industry has gone through numerous changes. Owing to its geographic and weather conditions, Brazil is well predisposed to grow sugarcane, from which ethanol fuel is produced at lower costs than from corn. Since its early days in the 1970s, the Brazilian biofuel industry has been primarily shaped by governmental policies. On the local retail fuel market, the Brazilian sugarcane ethanol has always competed with conventional gasoline whose regulated price has not always followed the world price. A single feedstock biofuel industry depends on annual harvests and crop yields. Unfavorable season may cause high sugarcane and ethanol prices resulting in intensified needs for foreign biofuel imports. Due to a supply shortage, Brazil imported about 1.5 billion liters of ethanol from the USA during 2011-2012.

As a part of national energy security, the Brazilian ethanol industry is expected to grow further. In early 2015, Brazilian government announced a new blending mandate increasing the ethanol share in gasoline from 25% to the new level of 27%. As of late 2014, Brazil was expected to generate as much as 26.9 billion liters of ethanol in 2015, a 5% increase from actual 2014 levels. Moreover, ethanol exports are projected to increase by 200 million liters reaching 1.8 billion liters in 2015. At present, flex fuel cars constitute some 55% of Brazilian fleet and the percentage is rising. In particular, more than 90% of new cars sold in Brazil are flex fuel vehicles. An 80% fleet share is expected to be reached by 2020 (Barros 2014).

4.2.2 US Ethanol

The biofuel–feedstock relationship of the US ethanol (Figure 7) gets a little more complex compared to the Brazilian scenario. Here, in this section, we explore the connections between the US ethanol and corn.

About 90% of the US ethanol is made from corn. In 2014, the US ethanol industry consumed almost 127 megatons of corn accounting for 40% of the US corn production

(Conca 2014). Compared to the Brazilian sugarcane industry, the US ethanol production from corn is a more technically demanding process. Simply put, corn crops first need to be converted to sugar before ethanol fuel gets produced. This implies higher production costs for the US ethanol.

Our results (Figure 7) show that the relationship between the US ethanol and corn consists of two strong dependencies of different kinds. We find significant coherence areas associated with both short term and long term horizons. First, a long term relationship approximately at the level of 500 days (almost 1.5 years) has been steadily present since the period following the food crisis of 2008. Second, its rightwards pointing phase arrows tell us that the US ethanol has been positively correlated with corn throughout the second half of the studied time frame. Third, we learn that corn leads the price of ethanol since the arrows are also pointing slightly upwards.

The other type of dependency is a collection of short term price interactions which are, however, much stronger compared to the Brazilian case. These time-limited episodes are associated with very high corn prices, e.g. the first food price crisis covered by our sample. During those events, the phase difference between the series decreases. Altogether, we find a stable long term relationship accompanied by several short term episodes associated with very high corn prices especially between 2010 and 2013. This supports the findings of the MST analysis which identified a strong and stable connection between the US ethanol and corn mainly during the later two periods, i.e. after 2008. Throughout the last decade, the relationship has always been positive with corn leading the price of ethanol. When the influence of crude oil is controlled for, we apparently lose a part of correlation. Especially the long term relationship between ethanol and corn gets somewhat reduced. However, other qualitative results do not get affected.

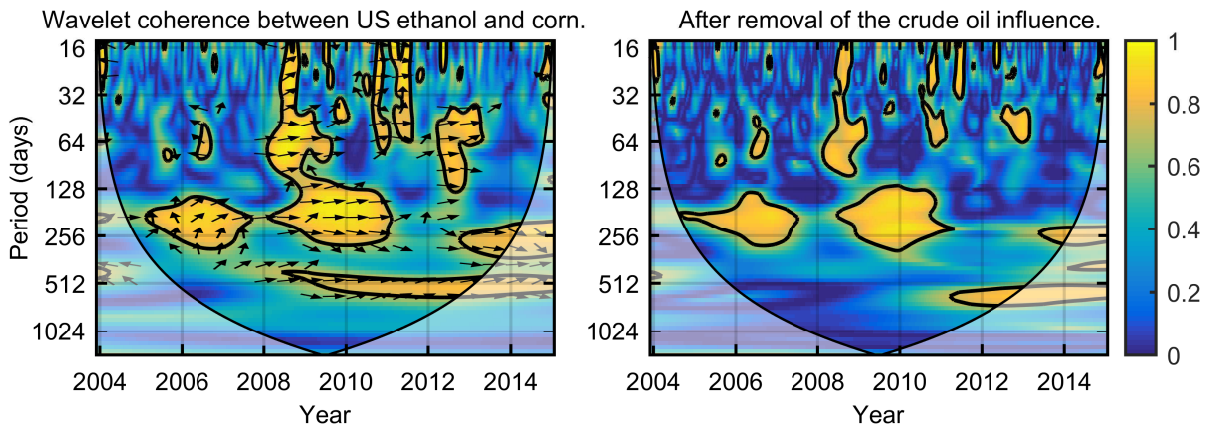
Since 2005, the US has maintained a position of the world's major ethanol-producing county, ahead of Brazil which used to be the previous leading ethanol producer for decades. In 2014, the US produced about 54 billion liters of ethanol. On the other hand, the US also represents the world's biggest consumer of oil. Based on the EIA statistics, the 2014 US consumption totaled 517 and 189 billion liters of gasoline and diesel, respectively. With recently expired tax credits and import tariffs, the biofuel industry has to face imports from Brazil, low crude oil prices and attempts to reduce the blending mandate.

4.2.3 European Biodiesel

The minimal spanning tree analyses indicated that biodiesel exhibited a price behavior different from both the US and Brazilian ethanol. It was poorly integrated into either of the constructed MST networks. Now we separately analyze biodiesel's connection to rapeseed. Associated wavelet coherence output is presented in Figure 8.

Unlike both major ethanol producing countries, the European biofuel industry builds on biodiesel. On energy basis, biodiesel represents approximately 80% of the total transport biofuels market. It was the first EU biofuel employed in the road transport starting from 1990s. At that time, biofuel's rapid expansion was driven by increasing crude oil prices and regulations such as the Blair House Agreement and resulting provisions on the production of oilseeds under the EU Common Agricultural Policy. Biodiesel has enjoyed generous tax incentives, mainly in Germany and France. The EU biofuels goals set out

Figure 7: Wavelet coherence: US ethanol versus feedstock



Wavelet squared coherence (*left*) and partial wavelet coherence (*right*)
 Coherence color spectrum shown at the right edge. Thick black curve marks
 significant regions. Phase differences are indicated by the directed arrows.

in the Directive 2003/30/EC, the subsequent Renewables Directive 2009/28/EC and the Fuel Quality Directive 2009/30/EC further pushed the use of biodiesel. Today, the EU is the world’s largest producer of biodiesel. With 10.9 billion liters generated in its 266 refineries during 2014, the EU itself accounts for about 45% of the world’s biodiesel production. The EU is also a primary consumer of biodiesel. In 2014, the EU consumption totaled 12.3 billion liters including 1.7 billion liters of imports (Flach *et al.* 2014).

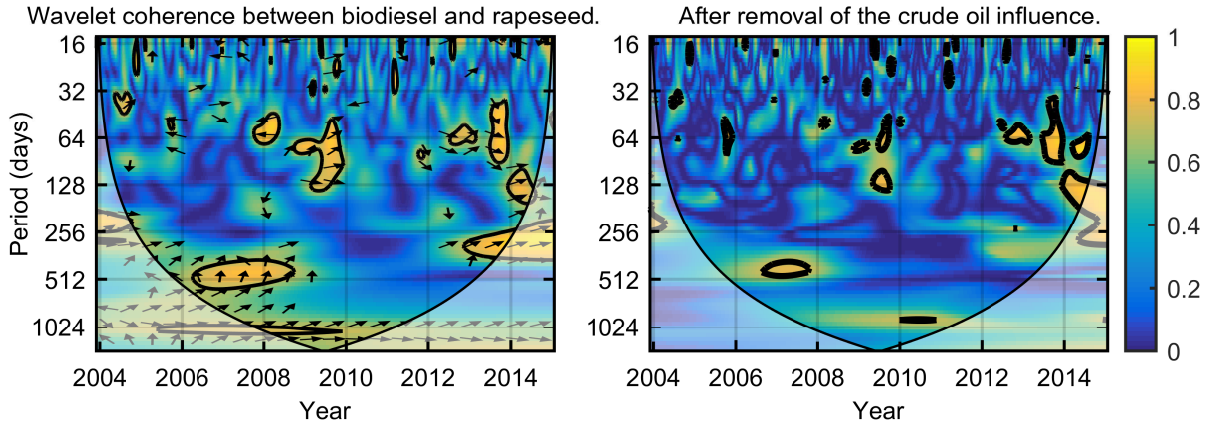
The fact that today’s EU biofuel market is dominated by biodiesel as opposed to ethanol is not random and it can be attributed to several government policies which shaped the European biofuel industry. As pointed out by Kristoufek *et al.* (2012), the EU and US biofuel targets follow different settings. The US requirements are set in volumes. In this sense, a liter of ethanol is considered the same as a liter of biodiesel. On the other hand, the EU blending rules are set in energy units. According to Hofstrand (2008), the amount of energy available from one liter of biodiesel equals to 1.54 liters of ethanol⁸. Historically, the European biofuel scheme has been designed so as to prefer biodiesel due to its considerably higher energy density.

In accordance with our previous MST findings, wavelet analysis does not yield much of a reliable relationship between the European biodiesel and its feedstock. However, when an occasional correlation appears, it is positive and biodiesel is being led by the price of feedstock. In case of rapeseed, we suspect certain dependency with a very low frequency (high scale). Unfortunately, this thin coherence island is mainly outside the interpretable area. Besides, we detect a few short lasting episodes of positive correlation. Specifically, we recognize a low frequency price interaction associated with the 2007–2008 food price crisis. Once controlled for the crude oil influence, effectively all the coherence between biodiesel and rapeseed oil disappears.

Similar results of low correlation between prices of biodiesel and prices of its feedstock are also characteristic for other feedstock besides rapeseed which we covered in

⁸According to Hofstrand (2008), 1 liter of biodiesel contains 32.6 MJ compared to 21.1 MJ in 1 liter of ethanol, energy considered in terms of net heating value.

Figure 8: Wavelet coherence: Biodiesel versus feedstock



Wavelet squared coherence (*left*) and partial wavelet coherence (*right*)
 Coherence color spectrum shown at the right edge. Thick black curve marks
 significant regions. Phase differences are indicated by the directed arrows.

our exploratory analysis (these results are available upon request) and which we do not report in this paper. There is no significant relationship between biodiesel and palm oil that would persist for longer than a year. Our unreported results for other feedstock commodities show that although we see several short lived positive price interactions, they do not allow for any strong conclusions. Exceptionally, there seems to be a positive stable relationship between biodiesel and sunflower oil. However, it appears to have been caused by their mutual ties to crude oil.

Compared to the results obtained for the Brazilian and US ethanol, we argue that the price of European biodiesel is very weakly connected with prices of individual feedstock commodities. Its price is primarily determined by a mix of factors including fossil fuels prices and the price behaviour of the whole oilseed cluster rather than only price of a single dominant feedstock. In this respect, the European biodiesel market substantially differs from the analyzed ethanol markets. The difference in the terms of close connection of EU biodiesel with fossil fuels, as compared to Brazil and US ethanol close connection to feedstock, may be explained by a key role played by government policies in the determination of biofuel prices. In the case of Brazil and US, the fossil fuel price is not determining ethanol prices because the well defined mandates (particularly strong in Brazil with the ethanol content of motor vehicle fuels being mandated as high as 27 percent recently) tend to isolate the fossil fuel markets and ethanol markets from each other. This was not the case in the EU where especially during the first period before the global food crisis the biodiesel tax exceptions played important role. Following the economic mechanism described in de Gorter *et al.* (2015); Rajcaniova *et al.* (2013), the continuing importance of co-movement of EU biodiesel and fossil fuels prices is also supported by nonexistence of EU-wide binding mandates as opposed to the situation in the US and Brazil.

4.3 Discussion

There are certain signs of a time limited positive correlation between biodiesel and its feedstock. During these episodes, feedstock led the price of biodiesel. Compared to the

results obtained for the Brazilian and US ethanol, we argue that the price of European biodiesel is very weakly connected with prices of individual feedstock commodities. In this respect, European biodiesel market substantially differs from the analyzed ethanol markets.

The US and Brazilian biofuel industries are dominated by corn and sugarcane, respectively. A single feedstock accounts for a vast majority of local biofuel production. In case of biodiesel, rapeseed oil represents the main feedstock from which up to 58% of European biodiesel is made. Rapeseed is followed by palm oil, which has become more important in recent years, especially due to large price discounts as reported by Flach *et al.* (2014). Nonetheless, during the analyzed period, no more than 2/3 of the EU biodiesel production was fed by one crop type.

In Brazil, there is effectively no possibility to switch for another feedstock. In the US, there exists a very limited possibility to switch from corn to wheat. However, this process is not flexible, it requires time and additional investments to technology. In contrast, the European biofuel production facilities can switch between several feedstock types including rapeseed, palm, soybeans or sunflower oil. These vegetable oils have similar consistency and can even be mixed with each other within the same production facility. In contrast to the major ethanol markets, the EU biodiesel industry enjoys a higher short term flexibility of production factors and better operates in the environment of fluctuating feedstock prices.

In 2015, the EU biodiesel production is expected to remain flat at about 11 billion liters. The EU domestic biodiesel consumption will likely continue in its slightly decreasing trend intensified by lower crude oil prices. In the next years, the demand for biofuels in the EU will be primarily shaped by mandates of individual member states. The most recent development of the EU bioenergy policies brought important changes in April 2015. The member states are still required to supply at least 10% of energy used in transport from renewable sources by 2020 (RED 2009/28/EC). However, the new legislation limits the share of energy coming from the first generation biofuels at a 7% level. In other words, the biofuels generated from crops grown on agricultural land cannot exceed 7% of energy used in transportation by 2020. Although a political compromise was reached, this April 2015 decision has its loud critics. Nonetheless, this political choice restores regulatory certainty and improves investors' understanding of the EU biofuel industry and its development until 2020.

Having analyzed the EU biofuel industry in the context of its main regulatory drivers, we conclude that European biodiesel plays a different role than the US and Brazilian ethanols do in their domestic markets. The difference has been demonstrated by the results of the MST and wavelet analyses. The European biodiesel industry does not depend on a single feedstock. In the same vein, our results show that biodiesel has been very weakly tied to its production factors. This result contrasts with strong biofuel–feedstock price co-movements we have found in both the US and Brazilian ethanol markets.

5 Conclusions

We have delivered an innovative research effort within the context of the biofuel economics. Our analysis has focused on the world's major biofuel markets – Brazil, the US,

and the EU. Present study covers 83% of the global ethanol production and about 45% of the biodiesel production. We have studied the relationships between ethanol, biodiesel, associated agricultural commodities, crude oil, relevant fossil fuels, and a group of financial assets. For this purpose, we have compiled a unique dataset containing 32 weekly price series. Compared to peer research attempts, our dataset is comprehensive and covers the 2003–2015 time period.

We have combined two methods that are still new to the biofuels literature. First, we have used the method of minimum spanning trees (MST) to classify and visualize a system of potentially biofuel-related commodities and assets. Such a broad attempt has not been undertaken in the literature before. Second, the identified biofuel–feedstock price pairs have been followed up using the wavelet analysis. We thus present the first attempt to combine the MST approach with the wavelet analysis within a single research application. The MST and wavelet analyses present a very suitable complementary pair of techniques. Given the technical possibility to include essentially an unlimited number of time series into the analysis, MST is very suitable as a first step of analysis. The wavelet approach used as the second step of analysis provides a more detailed description of the co-movement for the chosen pair of commodities with an advantage of localization of its time and scale characteristics.

In our MST structures, we have used several minor presentation innovations that were employed for the first time in the biofuel context. First, vertices of MSTs have been color-coded to allow for better legibility. Second, the length of constructed edges reflects their weight. Finally, our non-rectangular MST arrangement allows for visualizing complicated systems with a high number of items.

In accordance with our initial hypothesis, the resulting commodity systems get meaningfully structured. The interconnected networks consist of fuel and food branches. Generally, the food part includes clusters of vegetable oils, sugars, and cereals, while retail fuels and crude oil belong consistently to the fuel part of the system⁹. Our results show several crucial patterns.

We have demonstrated an important phase shift between Brazilian and the US/EU biofuel producing sectors. The Brazilian mature ethanol industry is characterized by a stable link between ethanol and sugar since the beginning of the studied time frame. The US ethanol market established a similar link between ethanol and corn with certain delay. In the same vein, a rise of the European biodiesel industry becomes visible in the late 2000s. While both the Brazilian and US ethanols have developed stable links to their primary feedstock commodities, biodiesel has reflected a different production logic. It has not become particularly tied to either of the relevant feedstock crops. Biodiesel’s unstable links confirmed it is not dependent on a single feedstock. On the contrary, biodiesel lively interacted with several commodities.

The subsequent wavelet analysis has reported a strong long term relationship between Brazilian ethanol and its feedstock. We have showed that the price of Brazilian ethanol was positively correlated with local sugar price and their relationship has been stable in time. Importantly, sugar led the price of ethanol throughout the period. The dynamics remained qualitatively unchanged when the influence of crude oil has been controlled for.

⁹Fundamental connections emerge already for weekly frequency presented in this paper. In the medium term (covered only in the exploratory part of our research and not presented in this paper) the networks get more structured as individual links shorten, the connections become closer.

We have found a similarly strong relationship between the US ethanol and its main production factor – corn. Their price co-movement consists of two positive dependencies. A long term stable relationship is accompanied by several coherence episodes at higher frequencies. These short run events coincide with periods of very high corn prices. We have found that corn led the price of ethanol across the frequencies. Moreover, the ethanol–corn relationship has proved to be robust to removing the influence of crude oil.

Finally, we have showed that the behavior of biodiesel contrasts with both major ethanol markets. In accordance with the previous MST taxonomy structures, we conclude that biodiesel and ethanol have different positions in the food-fuel system. Over the course of the last decade, we have seen a few short-lived price interactions between biodiesel and the analyzed feedstock crops. However, major European biofuel has not exhibited any strong co-movement with feedstock.

In summary, we have succeeded in confirming our initial hypotheses. First, we have described an interconnected system of the biofuel-related commodities. Moreover, we have commented on its evolution over the course of eleven-year period. Second, we have documented a phase shift that initially occurred between the mature Brazilian and belated US/European biofuel industries. Third, we have demonstrated a positive price co-movement of ethanol and its respective production factors. We have further showed that this relationship is stable in time with feedstock leading the price of ethanol. Finally, we have explained that the price of biodiesel did not depend on a single feedstock commodity. Biodiesel weakly interacted with several crops through more random price adjustments. Thus, the European biofuel industry substantially differs from both the Brazilian and the US establishments.

The decoupling of US ethanol from the fuels cluster as observed in our MST analysis illustrates an important role played by government policies in influencing biofuels prices. In agreement with biofuels policy theoretical models of de Gorter *et al.* (2015); Rajcaniova *et al.* (2013), the firm establishment of US ethanol mandates and suppression of tax incentives led to closer ties between US ethanol and its feedstock prices. Similar policy argument of gradual shift from tax incentives to mandates also explains the price co-movements of EU biodiesel. The results of our MST and wavelet coherence therefore show a significant impact of government policy decisions (in our case the choice of biofuels support instruments) on market transmitted price behavior.

The main contribution of this paper lies in its innovative and comprehensive approach and its policy relevance for the biofuels related policies of state and national government and major international bodies, including European Union. Employed methods make as few ex ante assumptions as possible. In particular, the wavelet coherence methodology represents a widely applicable model-free toolbox. Our findings contribute to the current biofuel policy discussion. Specifically, we stress the difference between ethanol and biodiesel production processes. Eventually, we shed some light on the biofuel–feedstock connections on the leading global markets.

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