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THE REGIONAL ECONOMIC IMPACTS OF BIOFUELS: A REVIEW OF MULTISECTORAL MODELLING TECHNIQUES AND EVALUATION OF APPLICATIONS

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The regional economic impacts of biofuels: A review of multisectoral modelling techniques and evaluation of applications

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Abstract

The regional economic impact of biofuel production depends upon a number of interrelated factors: the specific biofuels feedstock and production technology employed; the sector's embeddedness to the rest of the economy, through its demand for local resources; the extent to which new activity is created. These issues can be analysed using multisectoral economic models. Some studies have used (fixed price) Input-Output (IO) and Social Accounting Matrix (SAM) modelling frameworks, whilst a nascent Computable General Equilibrium (CGE) literature has also begun to examine the regional (and national) impact of biofuel development. This paper reviews, compares and evaluates these approaches for modelling the regional economic impacts of biofuels.

Keywords: biofuels; economic modelling; input-output; social accounting matrix; computable general equilibrium.

JEL codes: D57, D58, R13, R11.

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1. INTRODUCTION

Since the beginning of the 21st century, there has been rapid growth in the output of the global biofuels industry. Worldwide biofuels (bioethanol and biodiesel) production increased by 375% between 2001 and 2009 (US ENERGY INFORMATION ADMINISTRATION, 2011). However, this increase has been unevenly distributed across nations and regions of the world, reflecting a combination of different starting points and experiences of biofuel production technology as well as alternative policy support for the biofuels sector.

Continued growth of biofuels production is projected for the coming decades. The US is targeting a four-fold increase between 2008 and 2022 to 36 billion gallons, (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2010), while biofuels and other renewable fuels[1] for transport are mandated by the European Commission to increase to a minimum of 10% of energy in the transport sector in every member state by 2020 (EUROPEAN COMMISSION, 2011). Ethanol production is projected to increase by 70% in the decade to 2020 (OECD, 2011). The same report predicts that biodiesel production will increase by 138% over the same period, largely due to increases in Western Europe and large percentage increases in North and South America and Asia (OECD, 2011).

Biofuels production in each region will require significant resources from its host economies, in particular labour and land. A major report into "green jobs" by the United Nations Environment Programme (UNEP) argues that biofuel development will lead to jobs both in the agricultural sector and in fuel processing industries (UNEP, 2008)[2]. In the future, biofuels production is predicted to generate employment for over 9 million people in China alone (UNEP, 2008, p. 119). The specific employment impacts will depend critically, among other things, on the types of biomass produced – biodiesel feedstock, for instance, is typically harvested using more labour intensive forms of production than bioethanol feedstock (UNEP, 2008).

The UNEP report points to significant increases in the amount of land required for biofuel production. This would increase demand for a geographically immobile factor of production. Further adverse impacts could be felt on critical ecosystems – perhaps due to increased demand for water (OECD, 2011) – and on those communities who may be removed from land which is to be used to grow bio-feedstock (UNEP, 2008, p. 122). It would be expected that the potentially large changes in demands for factors of production across the world would lead to significant impacts on these regional economies.

The only robust method of assessing the impact of new, or changes to existing, biofuels production on the host regional economy is through economic modelling. The extent to which a regional economy is affected by hosting biofuels development will depend upon: the specific biofuels feedstock and production technology employed; its embeddedness to the rest of the economy; the extent to which new activity is created; and the structure and characteristics of the regional economy[3]. These issues are optimally analysed using a multisectoral approach. Such an approach is embedded in Input-Output (IO), Social Accounting Matrix (SAM) and Computable General Equilibrium (CGE) models. These models provide a method for analysis (e.g. "thinking through" the issues and scales of potential tradeoffs) and for policy formulation and design (e.g. comparing alternative policy options)[4].

This paper reviews multisectoral regional modelling methods and applications to biofuels production. These techniques have been widely used in the academic literature. An understanding of these modelling approaches is crucial, as the model results can only be considered to be robust when the underlying modelling assumptions are clearly stated and understood. For example, the choice of method may itself rule out some specific outcomes. This can also require addressing the key question of whether the modelling approach is able to capture specific, perhaps non-standard, features of the application (ISSERMAN, 2010).

There is a small literature summarising the limitations of assumptions in IO, SAM and CGE modelling in general (for instance, KOH *et al*, 1992; WEST, 1995), and the appropriateness of CGE modelling for regional economic development (e.g. PARTRIDGE and RICKMAN, 1998; 2010). However, the present paper is the first to evaluate multisectoral modelling approaches as applied to the regional impact of biofuels production. This review is informed by a detailed survey of applications from the academic literature using each of these methods.

The paper proceeds as follows. Section 2 describes the characteristics, general assumptions and limitations of the two "fixed-price" modelling approaches: Input-Output (IO) and Social Accounting Matrix (SAM); as well as one approach which can be considered a "flex-price" approach: Computable General Equilibrium (CGE). Fixed-price models assume that in response to an exogenous demand disturbance that there will be impacts on real variables (e.g. output, employment) with no change in relative prices (MILLER and BLAIR, 2009). In flex-price models demand and supply are modelled together, with prices and factor supplies allowed to adjust endogenously. Section 3 examines some of the specific limitations raised when these approaches are used to model biofuel production. Section 4 reviews the applications of these methods to specific biofuel schemes, focusing on the way in which the issues identified in Section 3 have been dealt with, while Section 5 directly compares the appropriateness of IO/SAM and CGE methods for biofuel production. Section 6 presents the conclusions.

2. MULTISECTORAL MODELLING APPROACHES: GENERAL EVALUATION

2.1 Useful characteristics of multi-sectoral modelling

Multisectoral modelling has three useful features. Firstly, shocks to economic activity may be specific to individual sectors. For example, changes in demand (or supply, e.g. increased efficiency) in one sector would not be experienced directly by other sectors. Secondly, multisectoral models use the interdependency of sectors in an economy (as represented by links in intermediate demand) to estimate the aggregate impacts on the economy of sector specific shocks. Finally, as well as aggregate effects, such models will identify the way in which this aggregate effect is distributed amongst individual sectors of the economy. Where sectoral "losers" are revealed by this analysis, appropriate policies to mitigate these losses can be designed.

2.2 *Fixed price modelling*

A set of Input Output (IO) accounts gives a snapshot of production activity in a specific area for a given period of time. It identifies the expenditure flows between production sectors in an economy, and the links between these sectors and exogenous final demand purchasers of output[5]. The "interindustry exchanges of goods" (MILLER and BLAIR, 2009, p. 2) are given in matrix T_1 of Figure 1. Each element in this matrix is identified as $x_{i,j}$ and is used to construct a matrix of technical production coefficients $a_{i,j}$. This is known as the A matrix. This expresses the intermediate inputs to sector *j* from sector *i* as a fraction of total gross inputs to sector *j*, so that $a_{i,j} = \frac{x_{i,j}}{X_j}$.

[Figure 1]

Given the structure of production identified in the IO table, IO modelling can be used to show the aggregate and sectoral consequences of increasing the exogenous final demand for the output of one sector. This increases the purchases of inputs from other sectors, which in turn increase the intermediate demand for the output of other sectors, and so on. The aggregate impact of a change in final demand is therefore greater than the initial stimulus, where the ratio between the aggregate impact and the initial stimulus can be expressed as a sectoral "multiplier" (MILLER and BLAIR, 2009). This type of IO technique is routinely used to estimate the possible knock-on economic impact of changes to the final demands for the output of industries located in the region. The modelling of new sectors/industries is discussed in Section 3.

The key equation for demand-driven IO analysis is then:

$$\Delta X = (I - A)^{-1} \Delta F \qquad \text{Equation 1}$$

where X is a vector of sectoral gross outputs, F is a vector of sectoral exogenous final demands. I is an identity matrix and $(I - A)^{-1}$ is the Leontief inverse[6]. Thus, changes in exogenous final demand drive changes in sectoral output through the Leontief inverse matrix. Sectoral multipliers are typically derived for "Type 1" (with household expenditures exogenous) and "Type 2" (in which household expenditure is endogenous) configurations[7].

A Social Accounting Matrix (SAM) builds on the data provided in a set of IO accounts by adding transactions and transfers related to the distribution of all income in the economy, not just income related to production (MILLER and BLAIR, 2009, Chapter 11). *T*he schematic SAM framework of Figure 2 shows how exogenous expenditures (f_1, f_2 and f_3) are used to determine the incomes of the endogenous accounts (y_1, y_2 and y_3). The SAM, explicitly identifies income links within an economy, for example, from the distribution of profits to households, and income repatriations from households to the external account. Further, a SAM model permits the identification of the impact of exogenous changes to transfers as well as changes to exogenous final demand.

[Figure 2]

By comparing Figure 1 and Figure 2 the additional data which are needed to move from IO to SAM accounts can be seen. These include, for example matrix T_{32}, which details income for household sector from factor payments, and matrix T_{33}, which gives the flows of income between institutions in the base year[8]. The matrix T_{11} is the same in the IO and SAM, with these coefficients being identical to those in the *A* matrix. Similar assumptions to IO are employed in "demand-driven" SAM modelling, so that many of the general criticisms that apply to one approach will also apply to the other (LOVERIDGE, 2004).

There are four general inter-related issues about the application of fixed-price modelling. Firstly, the assumed causal mechanism goes from exogenous final demands to output: there is no feedback working in the opposite direction from changes in the level of output to changes in exogenous final demand. For example, in fixed-price models there is no "crowding out" of exports or investment as domestic consumption rises as a result of an exogenous government expenditure shock.

Secondly, there are assumed to be fixed technical coefficients in production. This implies that production is characterised by constant returns to scale, i.e. if a sector's output increases by 10% then the demand for each of its intermediate and primary inputs also increases by 10%[9]. The sectoral output multiplier therefore gives the aggregate effect of *marginal* changes in demand for that sector, but it is calculated using existing *average* technical relationships. Further, the employment-output coefficients as given by the IO table are used to calculate the employment effects of demand changes.

Thirdly, these techniques assume there are also fixed coefficients in other relevant accounts. For example, in SAM analysis with government endogenous, changes in government income will cause the purchases by government from each of the industrial sectors in the region to adjust by the same proportionate amount, e.g. a 5% increase in government income will cause government base year demands for the outputs of each sector to increase by 5%. WEST (1995, p. 215) argues that fixed technical coefficients in such expenditure accounts are more "questionable" than for production sectors.

Finally, conventional fixed-price models assume an entirely passive supply side[10]. An expansion in final demand causes a "rippling" of additional production. At no point is there anything preventing the increase in the output of any sector required to satisfy the increased demand. There must therefore be no constraints on the ability of sectors to source intermediate or primary inputs (e.g. labour, capital, or other resources, which could include land). As WEST (1995, p. 215) notes, IO does "not consider resource supply implications" of shocks to exogenous final demands. A further implication of this assumption is that there is no inherent "switching" of resources between sectors in the face of increased demand: no sectors are required to contract in order that other sectors can expand.

Supply reacting passively to demand implies that supply curves for individual sectors are infinitely elastic at existing prices. This is consistent with extensive underutilisation of resources, such as significant underemployment of labour and excess productive capacity. Similarly, in a region which is able to expand labour and capital resources, through migration and investment respectively, such supply constraints could be non-binding in the long run (e.g. MCGREGOR *et al*, 1996). Therefore it has been argued that fixed-price methods are "useful in estimating long term impacts for small regions where full mobility of factors appears to be appropriate" (KOH *et al*, 1992, p. 33).

2.3 Flex-price modelling

In Computable General Equilibrium (CGE) models the economy is characterised by a set of equations describing the pattern of production, consumption and trade, where these equations are parameterised on an initial set of national or regional accounts[11]. Typically, equilibrium is characterised by a set of prices and quantities in which every market clears, i.e. demand equals supply for all commodities simultaneously. However, market imperfections can be incorporated so that some markets may not clear or prices can be determined in a non-competitive way. Such models have been widely applied in regional analysis but they are not dominant in the area (PARTRIDGE and RICKMAN, 2010). CGE models typically employ data from an IO table or a SAM. In calibrating a CGE model the base-year SAM is taken to represent an initial equilibrium for the regional economy (PARTRIDGE and RICKMAN, 2010). Whilst such calibration methods have been criticised (MCKITRICK, 1998) full econometric estimation would require time series data for every variable. These datasets are typically unavailable, particularly at the regional level.

As well as using IO or SAM databases, which give the initial production and distribution structure, CGE models also require complex programming of the behaviour equations, appropriate parameterisation, and an ability to interpret the results, which can be more difficult in CGE than IO/SAM modelling[12]. Understanding the results from many-sector, many-equation, flex-price models generally requires a greater familiarity with the specific nature of the economic interactions embedded within the model itself.

However, flex-price models have been developed because they provide a more general modelling framework than "fixed-price" methods. If the assumptions used in "fixed-price" models are imposed in a CGE model, this generates the same results as a corresponding IO/SAM model. In this sense IO/SAM models can be considered a special case of a CGE model in which production structures are characterised by fixed coefficients and factor supplies are infinitely elastic. In the case of CGE models, LOVERIDGE (2004) identifies the use of hierarchical production functions which allows inputs to each sector to substitute in response to changes in their relative prices.

Secondly, flex-price methods can deal explicitly with supply-side disturbances as they require the entire supply and demand for goods and factors to be specified. The modelling of factor use and factor prices can be crucial for the results of a CGE model. For example, the characterisation of wage setting can take many forms in regional CGE models. Some applications, arguably better suited for national models, use a fixed supply, while others have used a "wage curve" setup where wages are related to the bargaining power of workers (BLANCHFLOWER and OSWALD, 1994). Also in dynamic models, the way in which labour and capital stocks are updated over time, i.e. through migration and net investment, must be specified.

Factor prices are determined by the interaction of supply and demand in individual markets. The explicit specification of capacity constraints has been given as "the reason for choosing a CGE model" (WEST, 1995, p.217). With substitution between inputs and factors in production, for example, changes in relative prices can lead to changes in production technology. For example, other things being equal, an increase in the cost of labour would lead to a reduction in the amount of labour used in production.

It is likely that such issues will be resolved differently when the economy modelled is a region rather than a nation. Labour and capital mobility, for example, is greater at the regional level – i.e. workers typically face lower costs moving between different regions than between different nations. On the other hand, there may be additional rigidities in a regional model, for instance through some prices being set at the national level. A further complicating factor is the role of non-produced spatially immobile factors of production, such as land. This issue, which is important for the modelling of biofuels production, is returned to in Section 3.

3. SPECIFIC ISSUES FOR MULTISECTORAL MODELLING OF BIOFUEL PRODUCTION

This section focuses on four specific issues central to the modelling of biofuels production. Depending on the importance of these for the specific application, conventional application of these modelling approaches might need to be modified. Firstly, biofuel production uses as a major input a limited natural factor of production, land, which typically has alternative economic uses. Secondly, there may be expenditure switching, displacing some existing economic activity. Thirdly, biofuels production is likely to be a new activity for a region, rather than a sector/industry already represented in the economic accounts. Finally, we note that, in principle, an increase in biofuels production is a supply-side, rather than a demand-side, shock.

3.1 Land: Constrained in aggregate and mobile between sectors

The ability of sectors to expand to meet changes in demand for their output will be constrained by available resources. If the supply of factors of production is limited then the impact on economic activity will be reduced. We note that the cultivation of biofuels feedstock requires water, productive soil, other ingredients and access to local markets. This is likely to limit the geographical locations in which production can occur (LOW and ISSERMAN, 2009). One implication is that there may be (or is) a (future) binding constraint on land suitable for growing feedstock. Unmodified fixed-price approaches would not consider this, and so overstate the expected impact by predicting an equilibrium level of activity above that possible given available factors of production.

The existence of supply constraints can be introduced within demand-driven IO and SAM approaches. These work, however, by reallocating the demand for sectoral output, and therefore “mimic” the outcome of resource constraints, rather than systematically model the existence of those constraints. STEINBACK (2004) describes this general method. In the conventional approach final demand is exogenous and sectoral output endogenous. However, for sectors’ whose scale of production is constrained, perhaps because of factor supply restrictions or government regulation, output can be treated as exogenous and final demand endogenous. This could be used, for example, to show how a new biofuels facility may not lead to additional feedstock production, but may mean lower sales of feedstock to exports as intermediate demand for feedstock in biofuels production increases.

THORBECKE (1998, p. 306) discusses the unrealism of conventional multipliers in estimating the impact of exogenous demand changes in a SAM framework when output constraints exist in the agricultural sector (and are known). SAM applications have used “mixed multiplier” approaches, where the total multiplier is the sum of the sectoral (SAM) multiplier for output increases up to the constraint, and then the “mixed multiplier” for demand changes above this constraint (LEWIS and THORBECKE, 1992; PARIKH and THORBECKE, 1996).

In addition, fixed-price models assume a perfectly elastic supply of each factor of production. This implies that these models are unable to allocate scarce resources across uses. CGE models, however, with a fully-specified market for each factor of production, including land, which can accommodate a fixed aggregate stock of land that can move between sectors. We note, in particular, that land use changes are crucial for critiques of the environmental claims of biofuel production (SEARCHINGER *et al*, 2008; FARGIONE *et al*, 2008).

3.2 Displaced economic activity

Some economic activity may be curtailed as a result of biofuels production. This might come from the demand or the supply side of the economy. A crucial issue, from the demand side, is the extent to which expenditure on biofuels may come at the expense of existing spending on other fuels. The "cost" of biofuels production is therefore the lost activity supported by the previous spending. The "switching" of consumption might produce economic impacts that are considerable if the region currently produces transport fuels for domestic consumption (e.g. ALLAN *et al*, 2007). Clearly, if the biofuels are to be exported - or if they displace imports – from the region's perspective this offset will not need to be considered.

3.3 Introducing a new sector

3.3.1 Fixed-price

We will see in Section 4 that most of the fixed-price studies introduce a new biofuels sector into the economy. Two approaches can be used to introduce new industries in an IO (or SAM) framework: the "final demand" and "complete inclusion in the technical coefficients matrix" approaches respectively (MILLER and BLAIR, 2009, p. 634-636). If the new industry does not change the pattern of inputs used by other sectors in the region and if there is no offsetting constraint on the output of any sector, then both approaches should give the same impact. However, if biofuels production is to enhance energy security, we would expect that the inputs to other sectors would change, as fuel users purchased domestically produced biofuels rather than imported fuels[13]. Additionally, the use of (non-produced) inputs in biofuels production may mean that those are not available for other sectors, and so other sectors' output may be negatively affected.

To introduce a new sector in the technical coefficient matrix requires the addition of new rows and columns describing the pattern of its sales and purchases. The difference between base year and new levels of output can be credited to the new sector:

$$X^* = (I - A^*)^{-1} F^* \qquad \text{Equation 2}$$

where A^*, F^* and X^* are the extended A matrix, final demand matrix and gross output matrix respectively. The impact of the new sector on output is therefore the difference between the new level of output (X^*) and that as given in the IO table (X). The extent to which the new sector is embedded into the regional economy is captured through the $a^*_{i,j}$ ($a^*_{j,i}$) coefficients for the new row (column) in the A^* matrix. Varying the A and F matrices with A^* and F^* respectively, we can further decompose the change in output between changing technical coefficients and changing final demands.

3.3.2 CGE

The way in which bioenergy is incorporated in CGE models will be crucial for the simulation results. In their survey of (predominantly global) CGE models applied to biofuels KRETSCHMER and PETERSON (2010) identify three alternative approaches. The first is the "implicit approach", which "prescribes the amount of biomass necessary for achieving a certain production level" (KRETSCHMER and PETERSON, 2010, p. 674). DIXON *et al* (2007), for example, simulate the impact on the US economy of replacing

25% of crude oil inputs by biomass. In practice, this makes an "assumption [of] identical per unit costs of the two technologies [crude oil and biomass] [implying] a 33% reduction in the cost of producing biofuels between 2004 and 2020". KRETSCHMER and PETERSON (2010, p. 678) note that this approach – which making "strong and optimistic" assumptions about cost reductions – is "elegant" in that it circumvents many problems and doesn't require additional data.

The second approach is termed "latent technologies" – defined as "production technologies that are existent but not active in the base year of the model since their production is not profitable" (KRETSCHMER and PETERSON, 2010, p. 680). As relative prices change in a simulated scenario, these technologies can become profitable which initiates production in the sector. KRETSCHMER and PETERSON (2010) note that this approach can be used for "backstop" technologies that become profitable at specific prices. To parameterise these technologies, the modeller requires information on their input and cost structures, as well as the markup between production costs and the costs of substitutes.

The final approach identified is to disaggregate the bioenergy production sectors directly from the SAM around which the CGE model is constructed. KRETSCHMER and PETERSON (2010, p. 682) note that "this can be considered to be the most promising future approach… which should become increasingly feasible as more extensive and more reliable data on the growing biofuels sector become available". The accuracy of this approach is, however, "limited by insufficient data for the model base year and the fact that… there [is] little biofuel production and trade" (KRETSCHMER and PETERSON, 2010, p. 684). In comparing these three approaches, KRETSCHMER and PETERSON (2010) summarise their strengths and weaknesses. These are given in Table 1.

[Table 1 here]

3.4 *Supply-side changes modelled "as if" demand change*

The final specific issue is that increasing biofuel production, other things being equal, will increase supply of biofuels, reducing price and stimulating activity, potentially providing a lasting economic boost. With fixed prices in IO and SAM systems, this supply-side stimulus needs somehow to be modelled as an increase in demand for the output of the biofuels sector.

4. APPLICATIONS OF MULTISECTORAL MODELLING OF BIOFUELS

4.1 *Fixed-price applications*

Our search of the literature identified a total of nine academic studies use fixed-price methods to model the regional economic impact of biofuels developments: eight papers use IO and one uses SAM methods[14]. These are summarised in Table 2.

[Table 2]

From Table 2 we can see that five papers focused on regions within the US (VAN DYNE *et al*, 1996; SWENSON, 2006; SWENSON and EATHINGTON, 2006; HODUR and LEISTRITZ, 2008; and LOW and ISSERMAN, 2009). The focus of the four non-US studies is national economies in each case. In almost all of the applications, a new biofuels production sector is introduced which is then stimulated by an exogenous shock to its final demand. The only exception to this is CUNHA and SCARAMUCCI (2006), in which bioethanol production and harvesting activities are disaggregated from existing industries. It appears that no study has made an adjustment to the A matrix either to reflect increased energy security from sourcing fuel requirements locally rather than from imports or replacing currently locally produced fuels as intermediate inputs to regional production. This is surprising given that energy security is one of the principle rationales for introducing biofuels. The scale of production being modelled also varies across the studies. Intriguingly, all the North American (i.e. US and Canadian) applications consider the impacts of individual plants, while the other studies focus on larger scale changes in the production of biofuels, e.g. to meet national targets.

We can also see from Table 2 that in most cases, the results are based on a fixed-price method that has been modified in some way. These modifications are typically to take account of some of the issues raised in the previous section about applying these models, and their assumptions, to the specific case of biofuels[15].

SWENSON (2006) makes detailed "ad-hoc" adjustments to the results of standard IO modelling for a bioethanol facility in Iowa. This paper surveyed suppliers of commodities purchased by ethanol plants. Respondents to this survey stated that between zero and thirty per cent of the estimated IO employment change would be observed in practice. That is to say, they identify the marginal employment/output ratio as being below the average value. SWENSON (2006) therefore reduces by 75% the employment increase generated by the model in some sectors, i.e. electricity, gas supply, water, rail, and finance. The impact on employment given in Table 2 has therefore taken into account this "'reality check' adjustments" SWENSON (2006). However such adjustments raise questions about the appropriateness of IO modelling in general rather than for the specific case of biofuels.

This modification of IO results appears to be based on a short-run marginal perspective (as given by the survey respondents) being used to model a long-run economic result (such as that given by fixed-price models). In the short-run, with factors of production relatively fixed we would expect there to be limited effect on employment or capital employed in stimulated and indirectly affected sectors. In the long-run, i.e. once labour and capital (mobile factors of production) can move between sectors or between regions, Swenson's position suggests that the equilibrium production structure of the identified sectors would change (becoming less labour-intensive). This would, however, be unknowable *ex ante*. The simplest position (consistent with IO theory) would be to assume that its production structure was as given in the initial IO table. Further, it appears inconsistent to make such adjustments for some sector(s) but not others.

Secondly, some applications have considered "displacement" by introducing a negative demand shock at the same time as the positive demand shock to biofuels (VAN DYNE *et al*, 1996; THOMASSIN and BAKER, 2000[16]; KULIŠIĆ *et al*, 2007). This represents the lost economic activity that occurs when existing spending is reduced. Using KULIŠIĆ *et al* (2007) as an example of this approach, alongside the positive (exogenous) demand for a biofuels sector a negative shock is introduced to the final demands for the petroleum sector. The authors' argue that the petrol sector will contract as the biofuels sector expands to meet a given demand for transport fuels. The net sum of the (positive) effects of the biofuels shock and the (negative) petroleum shock give the aggregate effect. At the sectoral level, of course, not all the net impacts would be expected to be positive.

One key question therefore becomes the specification (e.g. the scale and the sectoral composition) of the offsetting demand shock. From the output multipliers reported for the biodiesel sector in KULIŠIĆ *et al* (2007) the positive stimulus is equal to a 492 million HRK change in the final demand for the biodiesel sector. The negative final demand stimulus to the petroleum sector is equal to 73.9 million HRK. The difference between these two demand shocks could be explained if a large amount of the expenditure on diesel in Croatia is on imported products (with currently only the margin on these purchases contributing to local activity). Switching to locally produced biodiesel, instead of imported diesel, would give this positive net economic impact to the Croatian economy.

Output constraints in individual sectors have been modelled (e.g. SWENSON (2006) and SWENSON and EATHINGTON (2006) (and, in a more formal setup, by LOW and ISSERMAN, 2009)). We understand that this is in an attempt to show that new biofuel production does not create new demand for agricultural production, but leads to a change in the distribution across intermediate and final demand of sales. As suggested above, this approach serves to mimic the outcome of a supply constrained agricultural sector. The first two papers apply a negative final demand shock to the corn sector, and a positive final demand shock for the new biofuels sector. These shocks are calculated in such a way as to ensure that the output of the (original) corn sector does not increase. In LOW and ISSERMAN (2009), rather than a negative final demand shock calibrated to achieve no change in output for output constrained sectors, these authors set the "regional purchase coefficient for corn" to zero. This "prevents new local corn production as a result of the ethanol plant's demand" (LOW and ISSERMAN, 2009, p. 83). In practice, this would be equivalent to assuming that the necessary demands for corn can be met by increased imports, rather than from local (supply constrained) sectors.

There is an important question that follows: if supply constraints on specific (non-produced) factors are a feature of the regional economy, how does this determine the maximum output for each sector? LOW and ISSERMAN (2009) and SWENSON (various years) consider that the output of the grain producing sector is fixed at its initial level. Such an assumption could be correct – in farming regions of developed countries, with higher productivity in agricultural production, it is perhaps possible that all major efficiencies have been exploited. This is not necessarily true for lower income countries, including developing regions. SAM multipliers can be estimated where sectoral output constraints are known in advance (e.g. THORBECKE, 1998), but these sectoral output constraints are necessarily imposed by the modeller. What is likely, however, is that sectoral output constraints are more flexible, reflecting the availability (and prices) of factors of production and sectoral production technologies. This requires a more sophisticated modelling approach.

4.2 *Flex-price applications*

In the same way as the IO/SAM applications discussed above, we summarise the academic CGE applications on modelling the economic impacts of biofuels[17]. Table 3 summarises the (six) single-region/nation studies[18].

[Table 3]

It is surprising from the academic literature seen in Table 3 that some of the studies do not include land as a factor of production (e.g. STEININGER and VORABERGER, 2003; DIXON *et al*, 2007; and GEHLHAR *et al*, 2010). Of the three papers which include land, this factor is typically modelled as a homogenous factor of production, available to the agriculture sector(s) and fixed in supply (i.e. GIESECKE *et al*, 2007; PERRY, 2008). PERRY (2008) assumes that other factors of production are similarly fixed: perhaps a sensible assumption in the case of a national economy. The importance of this assumption to that application is tested by carrying out two sensitivity simulations in which labour and capital are assumed to be characterised by infinitely elastic supply curves (but land remains fixed) and when all factors (land, labour and capital) are assumed to be fully adjustable.

Alternative treatments for land are more developed in CGE models of the global economy, and some of these have been applied to biofuels production. They are excluded from this review, however, which focuses on single-region/nation studies. One alternative treatment for land is to use a constant elasticity of transformation (CET) function in which land can be transferred between sectors, with the ease of transformation represented by the chosen substitution elasticity value. KRETSCHMER and PETERSON (2010) identify HERTEL and TSIGAS (1988) as the first use of a CET for land in a (global) CGE model, and this method is also used in BOETERS *et al* (2008) and KEENEY and HERTEL (2009). Clearly, the chosen elasticity value for the CET function is crucial and is derived from available econometric evidence or tested using sensitivity analysis to show the importance of the accuracy of the estimate chosen (e.g. BOETERS *et al*, 2008).

A further option is to "nest" levels of land use within a CET framework. BANSE *et al* (2008) adopt this approach, as well as incorporating a "land supply curve" which "models the relationship between land supply and land rental rate for each region and captures the idea than increased feedstock demand will have a larger impact on rents in land-scarce countries… which influences local biofuel production costs and hence their competitiveness" (KRETSCHMER and PETERSON, 2010, p. 676). A final option – adopted by GURGEL *et al* (2008) and building on the work of REILLY and PALTSEV (2007) – is to model five different types of land and assume that when land is switched between uses it takes on the productivity of that land type. This could more plausibly represent cases, for instance, where land is "zoned" or restricted in its use by planning laws.

5. EVALUATION OF MULTISECTORAL MODELLING APPROACHES

In this section we evaluate the usefulness and limitations of fixed- and flex-price modelling approaches for modelling biofuels. Our discussion is summarised in Table 4. Issues have been grouped to highlight the specific instances where each type of approach has a relative strength.

[Table 4 here]

Firstly, in fixed-price approaches the effect of new biofuels production is considered by determining the consequences for demand (both for the biofuels themselves and the demand for competing fuels, or other displaced expenditure) in the regional economy. We have seen that in applications these consequences could be introduced as "net" demand changes where positive demand disturbances for a new or existing biofuels production sector are offset – partially or completely – by reductions in demand for other fuels. In the biofuels market, however, a new biofuel facility would increase the supply of the good. This would typically be accompanied by a reduction in the price of the good (although the extent of this would depend on the nature of supply and demand elasticities). There may also be impacts on demand in other markets, but the initial stimulus would be on the supply-side. In a CGE setting, these adjustments – which are the natural implications of increased biofuel production – will occur endogenously.

Secondly, a CGE framework makes explicit the nature of the markets for all factors of production. For applications to biofuels, we have seen the importance of incorporating land into the analysis, given its key role in feedstock production, its alternative uses in existing agricultural production and the implications of land use changes. In a CGE analysis the supply and demand for factors of production will determine their price, whereas in IO/SAM approaches all factors are assumed to be available with infinitely elastic supply. As is noted in Section 2, modelling using conventional (i.e. demand-driven) IO analysis implies no impact on prices of goods or factor inputs.

As we have seen, however, some adjustments to the conventional IO approach – such as restricting the output of sectors which are assumed to be supply constrained – can approximate the effects of restricted resources. Much of the employment effect in URBANCHUCK (2007) employment effect from biofuels production is reliant on an expansion in the amount of feedstock produced (SWENSON, 2007). SWENSON (2006; 2007), SWENSON and EATHINGTON (2006) and LOW and ISSERMAN (2009) show how constraining the output of the grain sector reduces the economic impact.

Alternatively, some regions may not be constrained in the supply of available land (e.g. as is assumed in KULIŠIĆ *et al*, 2007 and CUNHA and SCARAMUCCI, 2007). As useful as these adjustments to the conventional IO approaches are, they merely mimic the outcome of resource constraints, rather than emerge endogenously from a model in which the use of factors is explicitly modelled.

In regions where biofuels feedstock production could compete with existing agricultural activities, introducing biofuels production might not increase land in use. Changes, however, would be expected in the pattern of (sectoral) land use, and this can only be captured endogenously within a CGE framework. At the regional level, available agricultural land is likely to be a binding constraint over all time periods and so different from other factors of production – labour and capita – whose supply can be augmented through investment and migration. The (fixed-price) passive supply-side assumption may be appropriate in specific instances, but is questionable for productive agricultural land, particularly in developed regions.

PARTRIDGE and RICKMAN (2010) argue that sectoral hierarchical production functions could include intermediate goods, capital, labour (separately identified as high- and low-skilled) and land. Land, in the model they outline, substitutes with a capital and (high- and low-skilled) labour composite input at the value added tier and does so with a relatively low elasticity of substitution. The supply of land in their model is allowed to respond positively with its rate of return, allowing for the total amount of land in use to increase (or decrease) in response to changes in land rentals. They allow land to be useable across all industries, but the rate of elasticity between industries "should be small" (PARTRIDGE and RICKMAN, 2010, p. 10).

The third general point is linked to the specification of markets for factors of production. In CGE models changes in the relative price of factors and input will drive changes in the production inputs to individual sectors. Factors move to their most valued use, i.e. as profit maximising sectors optimise their input mix. There are likely therefore to be positive and negative spillovers from a new sector entering a region. This could be caused by changes in the relative prices of goods as output in sectors with lower returns is “crowded out”. Sectoral “winners” and “losers” will be identifiable in a conventional IO/SAM analysis through the net impact of positive and negative changes in exogenous final demands. However, these sectoral effects do not arise in these models endogenously through competition over resources.

Fourthly, in CGE models (but not in fixed-price models) in principle it is possible to quantify the change in welfare which has resulted from the economic disturbance. As all agents and their behavioural assumptions are captured endogenously, their *ex ante* and *ex post* utilities can be compared.

Fifthly, and the first instance where fixed-price modelling has a relative strength compared to CGE, is in the incorporation of new economic activity. As we have seen above, in each of the fixed price applications where a biofuels sector does not exist in the region, a new sector is introduced into the IO or SAM accounts. This is done by specifying its linkages to other sectors, as well as requirements for primary inputs and sales to intermediate and final demand categories. By specifying the demands that the new activity places on local resources and sectors, one can estimate the aggregate impact on the regional economy, albeit with certain assumptions.

The introduction of a new sector into a CGE is not so straightforward. As we have seen, KRETSCHMER and PETERSON (2010) identify three approaches which have been used to introduce biofuels production into CGE models. Each of these has drawbacks and are typically more complex than those which have been used in the regional CGE applications to biofuels surveyed in this paper. Primary there is the level of uncertainty about the technology itself, its competitiveness with other fuels, how it might be assumed to enter sectoral production functions, and so on. All of these issues require careful consideration before the sector might be introduced into such models. The simplicity of the IO approach, on the other hand, is to abstract from these detailed considerations.

The final issue, related to that above, is that fixed-price approaches use conventional methods which are well understood and widely used in academia, government and private sectors. The concept of the multiplier is widely known, and generally understood to give a shorthand measure of the knock-on effects of an assumed disturbance on a whole economy. The variety of CGE modelling approaches and lack of a standard methodology means that the model structure will likely be crucial for results.

6. CONCLUSIONS

This paper has described Input-Output (IO), Social Accounting Matrix (SAM) and Computable General Equilibrium (CGE) modelling methods, reviewed applications of these to the economic impacts of biofuels and evaluated some of the strengths and weaknesses of these approaches for this specific application. Conventional IO and SAM models capture the embeddedness of an industry in an economy and are used to derive "multipliers". These have been used to quantify the economic impacts of changes in the demand for biofuels production. Such demand-driven applications however have general characteristics which mean that they, for example, assume prices remain fixed, and that supply side is entirely passive, meaning that sectoral competition over resources ("crowding-out") does not endogenously arise. This is unrealistic for biofuels which draw considerable resources from the economies hosting their production, particularly of feedstocks, labour and, critically, land. By assuming that there is some fixed level of output in "constrained" sectors, some fixed-price applications have attempted to adapt the technique to deal with this specific issue. It has been argued however that this "mimics" the outcome of factor supply restrictions rather than having this arise endogenously from the model itself.

Modelling first and second generation biofuels requires the explicit specification of land, and its use, as a factor of production. Biofuels development has been argued to have impacts on land prices, land use and food prices (e.g. MITCHELL, 2008). For this reason CGE models, in which markets for all factors of production can be specified appropriately for the regional economy under consideration, appear to offer significant benefits over fixed-price models. These would then permit prices and land use (in aggregate and by sector) to respond to market signals and so provide a more realistic modelling approach than fixed-price methods. Such an approach also allows for alternative specification of the factor markets. This should permit sensitivity analysis on the assumed nature of the relationship between land use as a factor of production and mobile inputs (e.g. capital and labour). Of course, greater complexity of modelling means that the additional value of a full CGE analysis should be carefully considered.

Further, this paper has implications for the appropriate modelling of third-generation biofuel technologies, such as those from marine algae (Mata *et al*, 2010). In one major difference to existing land-based feedstocks, the unintended impacts of "first- and second-generation" biofuels generated by changing land use may not apply to marine-derived biofuels[19]. SINGH *et al* (2011, p. 15) argue that "third generation biofuels from algal cells grown on non-arable land is the obvious answer to the food-fuel competition". NIGAM and SINGH (2011, p. 65) note that biofuels from marine algae "is a promising lead for new generation biofuels, without compromising with food supply as these can be cultivated on non-agricultural lands".

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FIGURE 1: Schematic layout of Input-Output table

		Expenditures		
		Production activities	Final demands	Gross output
Receipts	Production activities	T_{11}	$T_{13}+F_1$	Y_1
	Factors (i.e. labour and capital)	T_{21}	F_2	Y_2
	Imports	X_1	X_3+X_4	Y_X
	Gross inputs	Y_1'	$\sum (T_{13}+F_1+F_2+X_3+X_4)$	

Source: Adapted from THORBECKE (1998) by the author.

FIGURE 2: Schematic layout of Social Accounting Matrix

			Expenditures				
			Production activities	Factors	Institutions, i.e. Households and companies	External account	Total receipts
			1	2	3	4	5
Receipts	Production activities	1	T_{11}	-	T_{13}	F_1	Y_1
	Factors (i.e. labour and capital)	2	T_{21}	-	-	F_2	Y_2
	Institutions, i.e. Households, government, companies and capital.	3	-	T_{32}	T_{33}	F_3	Y_3
	External account	4	X_1	X_2	X_3	X_4	Y_X
	Total expenditures	5	Y_1'	Y_2'	Y_3'	Y_x	

Source: THORBECKE (1998), Table 7-2, page 301, adapted by the author.

TABLE 1: Three approaches of modelling bioenergy in CGE models

	Advantages	*Disadvantages*
Implicit approach	Elegant. Avoids breaking up the original model structure	No explicit bioenergy production sector. No commodity "biofuel". Trade in biofuels cannot be modelled
Latent technologies	More realistic representation of bioenergy production processes by including separate sectors Allows for trade in biofuels Allows for including new developments (second-generation biofuels, new producing countries, etc.)	Projections based on limited time series of biofuel production and trade data or even on pure assumptions Complex procedure, increase in computational burden
Disaggregating the SAM	*Ex-ante* inclusion of bioenergy technologies in underlying database Coherence of modelling framework	Full potential is at present restricted by data limitations Limitations to model new developments

Source: KRETSCHMAN and PETERSON (2010), Table 2.

TABLE 2: IO and SAM applications to biofuels, chronological order

	Paper	*IO/ SAM*	*Region(s)*	*Biofuel*	*How are shocks modelled?*	*Demand offset and/or a constrained sector?*	*Results (jobs, GDP)*
1	VAN DYNE *et al* (1996)	IO	Audrain county, Missouri (MO), USA	Biodiesel from oilseeds.	3 scales of production and final demand: 1. One plant in a single county; 2. 10% of the farm level diesel use in MO; 3. 25% of MO, farm diesel use.	Partially offsetting negative final demand shock to other industries – grain elevators, bulk fuel plants and local feed dealers. No constrained sector apparent.	Net jobs (and total regional household income) created by operations stage of 3 scales estimated at: 1. 1 ($25,000) 2. 13 ($312,000) 3. 31 ($780,000)
2	THOMASSIN and BAKER (2000)	IO	Canada	Ethanol from corn.	200ML fuel ethanol plant in Ontario with annual revenue of $123 million. Corn is new production and there is no reduction in final demand for gasoline in first scenario. Second and third cases have alternative demand scenarios which reduce impact.	Two variants to unconstrained IO scenario. Assumes corn is not all new production, with some reduction of exports of corn sector, and other domestic use of corn. Demand for corn-derived ethanol increases as in unconstrained case. Final demand for output of gasoline sector reduced (but margin on gasoline sale retained) alongside increased demand for corn-derived ethanol as above.	Without any demand offset:: $142M GDP, 2341 jobs created. In second scenario, impact falls to $84.2m GDP, 1390 jobs, while in third, impact of $26.9m and 439 jobs.
3	SWENSON (2006)	IO	Three county region of Iowa, USA	Ethanol from corn	New final demand of $118.6million for new ethanol sector.	Offsetting negative shock to final demand for corn sector such that there is, in effect, an output constrained corn sector.	Direct effect: 35 jobs, $18.4m Indirect effect: 75 jobs, $6m Induced effect: 23 jobs, $0.9m Total: 133 jobs, $25.4m
4	SWENSON and EATHINGTON (2006)	SAM	Three county region of Iowa, USA	Ethanol from corn	New final demand of $118.6 million for new ethanol sector, with profits retained locally either through increased spending on investment.	As in SWENSON (2006) above, reduction in demand for grain sector in region in order for there to be no change in output of this sector.	Each additional 25% of local retention of profits raises regional outputs by $1.2 million (if spending increases) or $2.7 million (if investment increases) from those in Swenson (2006).
5	CUNHA and SCARAMUCCI (2006)	IO	Brazil	Bioethanol from sugar cane produced using two technologies and two harvesting methods	R$95.22 billion additional final demand for ethanol sector (828% increase in output of sector, in line with Brazilian ethanol supplying 5% of anticipated global gasoline demand in 2025).	No offset to final demand or constrained sector.	Brazilian GDP up R$154 billion (11.4% from 2002 level), "occupied people" up 5.3 million (8.0%), including the construction and operations stages.

6	KULIŠIĆ *et al* (2007)	IO	Croatia	Biodiesel from rapeseed oil	Increased demand for new sector equivalent to (hypothetical) doubling of the share of biodiesel in diesel consumption in Croatia from 5% to 10%.	Negative demand shock to Croatian diesel sector to take account of "switching" of source of diesel. Assumes rapeseed oil grown on agricultural land, so no offset to existing food production.	Net (National) income up HRK 1,066.5 million and employment up 1,947.
7	HODUR and LEISTRITZ (2008)	IO	North Dakota, USA	Ethanol from corn and cellulosic ethanol	New ethanol production and construction of facilities.	None apparent.	Corn ethanol facility (50MGY) creates secondary employment of 497, and direct and secondary impact of $45.8 million. Cellulosic ethanol facility (50MGY) creates secondary employment of 2400, and direct and secondary impact of $185.2 million
8	LOW and ISSERMA N (2009)	IO	Four counties in US Midwest and hypothetical facilities, USA	Ethanol from corn	New facilities sited locally, consuming inputs from local economy, and which pay (a small) premium for corn.	Output of grain sector constrained to initial level to mimic no new grain production as a result of change in demand from biofuels production.	Employment effect varies between sites from 99 to 250 jobs, regional output up by between $137m and $248m
9	FERNAND EZ-TIRADO and PARRA-LOPEZ (2010)	IO	Spain	Ethanol from cereal and biodiesel from sunflower oil.	Impact of one tonne of oil equivalent increased demand for biodiesel and bioethanol on Spanish economy during operational phase. Impacts of (temporary) construction phase also modelled for each technology.	No constraints on the output of any sector.	When more than half of the feedstock is imported, biodiesel production has a greater impact than bioethanol. This result seems to draw an interesting link between economic impact and increasing fuel security.

TABLE 3: Single-region/nation CGE applications to biofuels, chronological order (alphabetical for papers published in same year)

	Paper	*Region(s)*	*Static/dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
1	STEININGER and VORABERGER (2003)	Austria	Static	Not separately identified. Factors of production included are energy, labour and capital.	One of thirteen biomass uses considered is rapeseed methyl ester (RME) and recycled edible oil methyl ester (ME) which can substitute for diesel consumption. Supply curves give future costs and availability.	Subsidising biofuels individually (i.e. but not other biomass uses) allows for GDP and employment effects from changing production patterns.	ME expansion, "possible at costs close to the fossil diesel reference price (ibid, p. 371), produces net positive employment impacts by 20 year horizon, small (sometimes negative) GDP effects and reduced CO2 emissions.	No land constraint used, although labour constraints discussed with particular relevance to the Austrian economy.
2	DIXON *et al* (2007)	USA	Dynamic	Not explicitly included.	Biomass used in petrol refining comes from corn.	Business as usual (i.e. no biofuels policy after 2004) scenario for 2020 compared with alternative scenario in which there is substitution of biomass for crude petroleum and 2020 biofuels targets are met.	GDP higher by 0.158% ($18 billion) in 2020 compared to benchmark, with employment up by 17,500 (0.013%). Labour is not assumed exogenous as "biomass substitution generates a strong long-run increase in agricultural employment, about 35,000 extra jobs in agriculture in 2020. We think that this will have the effect of keeping farmers in work who otherwise would have retired or would have worked their farms less intensively... (ibid, p. 8-9).	No land constraint applied.

3	GIESECKE *et al* (2007)	Brazil (disaggregated into regions)	Comparative static (long-run national closure with employment rate exogenous, but capital endogenous, land to agriculture fixed in aggregate)	Total land available for all forms of agriculture held fixed. Land for manual harvesting fixed, but land for mechanical harvesting allowed to expand.	Ethanol can be produced in distilleries and "combined sugar-ethanol plants".	Foreign demand for Brazilian ethanol increased by 184% (consistent with forecasts for export growth between 2007 and 2020 and domestic demand increase of 114% between 2007 and 2020, reflecting rising share of biofuel use and increased preference for car transport over same period.	Growth in domestic ethanol demand drive results, rather than export increases (which begin from small base). Contractions in output of food processing sectors is observed due to flow of land out of agriculture increasing costs. Appreciation of real exchange rate due to increased exports causes crowding out of other exports.	Authors report that "in policy debates on this issue, pressure for further land clearance is often associated with the rapid ethanol growth scenario. However, we found that the amount of land that must shift from other agriculture to mechanical harvesting is small, relative to the amount of land presently used in other agriculture" (GIESECKE *et al*, 2007, p. 15).
4	PERRY (2008)	Argentina	Static	Land, labour and capital fixed in first simulation, with two alternative scenarios in which 1) land is fixed, but labour and capital supply is infinitely elastic, and 2) supply of all factors is infinitely elastic (at initial prices). Factors of production are homogenous with no costs to moving between different uses.	No biofuel production, but agricultural sectors identified and stimulated to mimic increase in world demands for bioenergy crops.	Increased world prices for agricultural goods (differentiated by commodity) from literature.	Ability of land use to respond to increased world prices for biofuel feedstocks are crucial for impact on production and economy of Argentina. Without land use or labour force expansion (perhaps appropriately for a national economy) the real wage unambiguously declines,	Factors of production constrained in some simulations, especially land.

5	ARNDT *et al* (2009)	Mozambique	Dynamic model with growth in labour, capital and land productivity growth assumed with adaptive expectations.	Land is used in agricultural sectors and "land supply" is assumed to grow at 2% per year over simulation period, reflecting previous productivity increases.	Creation of sectors for "sugarcane" (for ethanol) and "jatropha" (for biodiesel) with dedicated processing sector for each.	Exogenous increase in amount of land allocated to each feedstock sector introduced over the simulation period in line with expert guidance. Biofuels produced solely for export.	GDP growth increases by 0.6% over baseline scenario with both sugarcane and jatropha development.	Paper reports that "access to large, contiguous pieces of unused land is limited by insufficient road infrastructure, meaning that it is unlikely that biofuel investments will be undertaken entirely on new lands" (ARNDT *et al*, 2009, p. 94). Expert judgement informs assumption that 50% of production of biofuel crops takes place on currently unused land.
6	GEHLHAR *et al* (2010)	USA	Dynamic	Not explicitly included.	Bioenergy and biofuels sectors – including "corn based ethanol, cellulosic ethanol and other advanced biofuels" (GEHLHAR *et al*, 2010, p. 173).	Reference and alternative scenarios compared, as in DIXON *et al* (2007). "Reference" scenario for 2022 with assumed 8 billion gallons of ethanol. Alternative simulation assumes 36 billion gallons biofuels, 15 billion from corn ethanol and 21 billion from "non-conventional sources". Price reductions in ethanol compared to increased oil prices. Sensitivity analysis shows impact of high and low oil price assumptions, and with and without tax credits.	GDP higher than reference case in both oil price scenarios without tax credits and lower in both oil price scenarios with tax credits. Declines in exports across all scenarios with increases in price and public consumption and investment. Increase in real wage, however employment results not reported.	No land constraint applied.

TABLE 4: Strengths and weaknesses of IO/SAM and CGE approaches for modelling regional impact of biofuels production

	IO/SAM		*CGE*
Weaknesses	Supply shock modelled as demand shock(s)	Strengths	Accommodate both demand and supply side shocks
	Supply of all factors of production, including land, typically assumed infinitely elastic at existing market price		Availability of factors of production modelled explicitly, with markets determining price.
	Sectors do not compete over factors of production		Factors of production move to sectors where return is greatest
	Welfare impacts cannot be compared		Welfare impacts of changes can be evaluated
Strengths	Demand for local resources explicitly modelled	Weaknesses	Difficult to parameterise and introduce new sectors
	Link between new demand and aggregate impacts are estimated using accepted methods		No standard methodology makes assumptions in model structure (e.g. parameterisation, closure rules and behavioural assumptions) crucial for results.

Appendix A: Global CGE applications to biofuels, chronological order (alphabetical for papers published in same year)

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
1	REILLY and PALTSEV (2007)	Global, disaggregated into 16 regions	Recursive dynamic	Land can be used across agricultural sectors. It is modelled as a "non-depletable" resource, with exogenously augmented productivity improvements.	Electricity production from biomass and liquid fuel from biomass are introduced using "latent technologies" assumption. Both technologies use land in their production, and compete with other agricultural sectors.	Three alternative scenarios for cumulative USA emissions allowance allocations are constructed, with alternatives in which trade in biofuels is or is not possible.	No employment or GDP results are presented, but agricultural exports are reported. In cases where trade is possible, low targets for US emissions with biofuels production in other countries increase the exports of US agricultural products. Without biofuels exports, US becomes a net importer of agricultural products.	No sensitivity to land constrant, but results for scenario where biofuels is restricted to that produced domestically, US biofuel "substantially displaced petroleum products, accounting for nearly 55% of all liquid fuels in the USA… This would require about 30% of all USA crops, grass and forestland" (REILLY and PALTSEV, 2007, p. 13).
2	BANSE *et al* (2008)	Global (disaggregated into 37 regions)).	Static model with reference case growth assumptions.	Changes GTAP model from assuming imperfect substitution between different land uses to "three-level constant elasticity of transformation-structure that takes into account differential degrees of substitutability between types of land" (BANSE *et al*, 2008, p. 145). Further, agricultural land supply (normally exogenous in GTAP models) is modelled using a land supply curve "specifying the relationship between land supply and a land rental rate".	Production structure extended to incorporate substitutability between oil, petrol and ethanol (from sugar beet/cane or cereals) in petroleum sector. Ethanol produced from four options, with substitution possible in response to relative price differences – sugar beet, wheat, grain and forestry.	Model impact on national and international markets of EU biofuels policies. Subsidy to petro-industry reduces input prices for biofuel inputs, stimulating their demand. Budget neutrality maintained by offsetting cost of subsidy by tax on use of petrol. Biofuel scenario considered for 5.75% blending in 2010 and 10% in 2020 against a reference scenario with no obligatory biofuels blending. Alternatives to both these scenarios assumes high oil prices.	With biofuels blending world agricultural prices rise relative to reference scenario, stimulating increases in feedstocks for biofuels (oilseeds). Biofuel targets in EU being met "at the expense of biofuel consumption in non-European countries" (BANSE *et al*, 2008, p. 129). EU targets not met without blending targets, "even under a scenario with a strong increase in crude oil price" (BANSE *et al*, 2008, p. 129). Agricultural land used for biofuels in EU rises to 7.3%, with price of agricultural land increasing by between 5 and 20% by 2020.	Land supply curve a novel feature, allowing for areas with little pressure on land to show increases in use of land with modest rental increases, but "land-constrained" regions to see larger increases in land prices when agricultural demands change.

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
3	BIRUR *et al* (2008)	Global (GTAP-E) model, with 18 regions.	Recursive dynamic	Land enters production hierarchy at value-added nest with AEZ for each type of land use, with nested substitution between AEZs for a given use of land.	Three biofuels production types (first and second-generation ethanol and biodiesel) complementary goods to petroleum production in production industries, and biofuels composite substitutable with petrol in household consumption.	Three biofuel specific shocks entered to attempt to project biofuels economy between 2001 and 2006. The shocks are the experienced increase in oil prices; the introduction of ethanol as a gasoline additive; and subsidies to EU and US biofuels production. Model predictions are compared to actual outcomes observed in biofuel producing regions.	Model calibrated to produce the observed increases in biofuels production, however model reproduces much of the changes in the biofuels and wider economy seen between 2001 and 2006 with three shocks entered. The share of US corn going to ethanol by 2006 in the model (6.8%) is, for instance, very similar to that observed (6.5%). "Overall the model predicts the stylized facts about the structure of the energy, biofuel and agricultural economy reasonably well" (BIRUR *et al*, 2008, p. 26).	Oilseed acreage in EU increases by 15%, at the expense of all other land-using sectors, with other regions seeing declines in other types of land use with impacts on other sectors using these land types.
4	BOETERS *et al* (2008)	"Worldscan" global general equilibrium model	Recursive dynamic	Land types of arable and forestry combine in model, with a Constant Elasticity of Transformation of 2.0 in base case.	Five biofuel production technologies (one for biodiesel and four for ethanol) introduced in model	Baseline scenario of exogenous factors growth (e.g. population, GDP, Energy consumption, emissions, energy intensity, CO2 intensity) to 2020 and alternative scenarios in which EU policy target of 10% biofuel share in 2020 is met (alongside other regions biofuels targets) and in presence of EU-ETS.	The "emissions price of the EU-ETS is hardly affected when various targets for the share of biofuels in transport fuels are imposed". A 10% biofuel target increases world arable land price, food prices slightly, with a marginally positive change on economic welfare, but no significant impact on emissions.	Sensitivity analysis shows that higher elasticity of transformation of land (between arable and forestry uses) results in lower land rents and higher welfare (although "in quantitative terms, the differences… are hardly noticeable".
5	GURGEL *et al* (2008)	Global, disaggregated into 16 regions (EPPA model)	Recursive dynamic	Land treated as a renewable resource (i.e. non-depletable) with five land types (crop, pasture, harvested forest, natural grass and natural forest). Crop sector and two biomass sectors (fuel and electricity) can compete over cropland. Land resources can be altered through conversion or abandonment.	"Latent technologies" of which bio-oil and bio-electric use biomass to produce a liquid fuel and electricity respectively. Production of "advanced technologies" enters when costs become competitive to existing technologies.	Reference scenario in which biofuels enter due to increasing oil price making ethanol competitive and two alternative scenarios with GHG emissions targets in developed and developing countries by 2050 (cumulative emissions "approximately consistent with 550 ppm CO2 stabilisation goal".	Agricultural and food price index increase between 1994 and 2050 by between 5% and 10%, with larger increases in forestry products. Land rents increase across all land types, with the area of land required for biomass crops between 1.5 GHa (similar to global levels for crops today) and 2.5 GWh.	With land supply elasticity, there was "much less conversion of land from natural areas, forcing intensification of production" (GURGEL *et al*, 2008, p. 36). Results "emphasise the importance of how the non-market value of land is reflected in the conversion decision" (GURGEL *et al*, 2008, p. 37).

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
6	HERTEL *et al* (2008)	Global, disaggregated into regions.	Recursive dynamic	Forest, pastureland and cropland types of lands distinguished in model. Land use allocation occurs in two stages: 1) landowner allocates land cover across three different types (named above), 2) given availability, crops are allocated to land types. Constant elasticity of transformations used to represent ease of which land can be shifted between uses.	Corn-based ethanol, sugarcane-based biodiesel and oilseed-based biodiesel disaggregated from usual GTAP database by TAHERIPOUR *et al* (2007) which substitute with petroleum products in consumption (apart from corn-based ethanol which substitutes with fossil fuels to petroleum refining).	Subsidies on biofuel use iterated to produce renewable fuel shares mandated for 6.25% of fuels in EU by 2015 and 5.1% in US.	Impacts on policies in EU and US can be shown separately and jointly. For instance, US oilseeds production increases by 7.7% "mainly due to the influence of EU policies on the global oilseeds market" (HERTEL *et al*, 2008, p. 25). Increased cropland comes at expense of pasturelands (down 9.4% in Brazil alone). Welfare effects negative at global level (-US$43billion), principally due to terms of trade loss in oil exporting countries (-US$25billion) and efficiency loss in EU (-US$24billion). Some positive welfare changes in rest of world (i.e. non-US, EU or Oil exporters).	Land constraints in each AEZ and region crucial for results, and heterogeneous in results.
7	KRETSCHMER *et al* (2008)	DART model of global economy, disaggregated into 19 regions.	Recursive dynamic	Land not included.	Seven latent bioenergy technologies, with cost structures identified from literature, and markups to fossil energy taken from IEA and other sources. Biofuel and bioethenoal substitute perfectly for conventional diesel and gasoline respectively.	A reference scenario in which EU biofuels production remains at (2005) current levels, and two alternative scenarios in which biofuels take a 10% share met through domestic only or domestic and imported biofuels.	Policy support (such as quota) required to develop bioethanol and biodiesel sectors in EU. EU becomes larger producer of ethanol than US under quota (but no US policy is modelled). Welfare effects for EU are "ambiguous", as some countries (Germany and Eastern Europe) negatively affected, while others see increase (Scandinavia and Mediterranean areas).	-
8	TAHERIPOUR *et al* (2008)	Global, disaggregated into 18 regions.	Recursive dynamic	Follows LEE et al (2005) in using AEZs for each of the land using sectors.	By-products from biofuels added to model as substitutes for animal feeds, and that ethanol and biodiesel industries produce fuels and their by-products.	Same simulation as HERTEL *et al* (2008), but compare results including biofuels by-products to those without. Scenario compares outcomes in 2015 under alternative model configurations.	Including biofuel by-products into global CGE model, the authors report "smaller changes in the production of cereal grains and larger changes for oilseed products in the US and EU, and the reverse is true for Brazil… Finally, it shows that studies that ignore by-products may be misleading in their estimates of land use and land cover changes due to biofuel mandates.	Paper acknowledges that past studies "have overstated the impact of liquid biofuels on agricultural markets due to the fact that they have ignored the role of by-products resulting from the production of biofuels" (TAHERIPOUR *et al*, 2008, p. 7).

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
9	BRITZ and HERTEL (2009)	Global CGE model, augmented with partial equilibrium model for agriculture providing supply elasticities	Recursive dynamic CGE model	Land use augmented using Agro-Ecological Zones following LEE *et al* (2005).	Biodiesel production disaggregated in GTAP model, but not ethanol, as modelling intention is to show linking between agricultural and economic models, with "stylised" biofuels scenario.	EU biofuels target for biofuels assumed to be met through biodiesel production. CGE model produces impacts on land use changes, emissions, and prices and quantities for commodities. These are fed back into the agricultural model to get detailed (i.e. country-level and smaller) EU impacts on land use and land nutrient measures.	Returns to cropland increase, causing cropland expansion, largely at the expense of pastureland. Large increase in cropland cover in EU and reduction in EU net exports of oilseed and oils due to EU target.	No specific sensitivity analysis on land described.
10	KRETSCHMER *et al* (2009)	Global model calibrated to GTAP for 2001 of 12 regions, 7 in EU.	Recursive dynamic	Land supply fixed in each country.	Latent technologies, active from 2005 onwards (base year of model 2001). Biodiesel and ethanol substitute for conventional diesel and gasoline	Subsidies on biofuel production in each producing region so as to hit 2005 biofuel production levels in reference case (consistent with EU 2020 emissions target with no additional biofuels). Alternative scenarios with higher biofuels targets in (each and all) EU countries, and additional renewable electricity targets, all for 2020.	EU climate targets, with no biofuels targets, are not sufficient in making biofuels competitive with fossil fuels. EU biofuels production reaches levels of Brazilian production in 2020 with 10% target. When EU as a whole has 10% target (but rates differ across countries of EU) production increases in Mediterranean countries specifically, with smaller EU welfare losses. Overall welfare losses in EU relative to 2020 with no additional biofuels ranges between -2% and -4.5%.	"The demand for biofuels augmented by the 10% target considerably affects its trade flows, most strongly for the EU and for Brazil… there is heterogeneity in competitiveness of the biofuel sectors within EU regions,… Agricultural prices are significantly increased with the biofuel target, providing some ground for the concerns expressed in the 'food vs. fuel' debate" (KRETSCHMER *et al*, 2009, p. S293).
11	MELLILO *et al* (2009)	EPPA global model (16 regions), and Terrestrial Ecosystem Model	Recursive dynamic CGE model, with climate model	Three land classes in CGE model given a unit price, and then land value changes drive changes in the land area required for alternative uses in each region. Land useable five sectors, including biomass and liquid fuel from biomass.	Emissions projections drive atmospheric model which produces impacts on agricultural productivity which are fed back into CGE model. Biomass fuel sector produces a perfect substitute for refined oil.	Two scenarios with "same limit on industrial and fossil fuel GHG emissions", the "deforestation" scenario is consistent with clearing of forests for biofuels production, or clearing of forests to move arable production displaced by biofuels.	Over 11% of earths land area is used for biofuels production in "deforestation" scenario, with growth in cropland and small reduction in amount of pasture. In "intensification" scenario, smaller increase in use of land for biofuels, but larger decline in pastureland. Slightly lower food production in "intensification" scenario.	Increasing impact of human activities on use of world resources "can be attributed to the production of biomass for cellulosic biofuels" (MELLILO *et al*, 2009, p. 11).

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
12	TAHERIPOUR *et al* (2009)	Global, disaggregated into 18 regions.	Recursive dynamic	Total land supply fixed in each country, but can change between alternate uses (i.e. "forestry", "cropland", "dairy farms" and "other ruminant").	Expands HERTEL *et al* (2008) with amendments to ethanol production technologies in the US and EU, the "other food products" and "vegetable oil sector", an explicit biodiesel production technology.	Biofuels mandate of 15 billion gallons of corn-based ethanol in the US and 6.25% of transportation fuel in the EU, both in 2015. Forecast for world economy from 2006 to 2015 in baseline scenario, compared to one where both US and EU have 2015 mandate met.	Production of biofeedstocks in biofuels production countries increases "sharply", with production of some other crops in these countries falling. "Biofuel mandates alter the production pattern of agricultural commodities within biofuel producing regions".	Mandated biofuels targets "are expected to increase croplands and reduce forest and pasture land in almost all regions of the world, with few exceptions" (TAHERIPOUR *et al*, 2009, p. 17). Food production in most regions is reduced due to cropland changes, with grazing land reduced. While changes due to mandates on the livestock industry are "important", "they do not harshly curtail these industries" (TAHERIPOUR *et al*, 2009, p. 23).
13	YANG *et al* (2009)	The five countries of the Greater Mekong Subregion (GMS) (Cambodia, Lao PR, Myanmar, Thailand and Vietnam)		Follows BANSE *et al* (2008) in allowing cultivated land substitution between agricultural sectors. Cultivated land supply assumed to be fixed.	Biofuels production sectors added to the GTAP model used to distinguish biofuel feedstocks (maize, soybeans, cassava) and biofuel industry sectors (sugar ethanol, corn ethanol, soybean biodiesel and rapeseed diesel)	Biofuel production assumed to meet 2020 targets in two scenarios: 1) USA, EU and Brazil and 2) USA, EU, Brazil and GMS. Third scenario assumes high world oil prices and high substitutability of biofuel and gasoline. Production levels met by introducing a price subsidy to biofuel industry and iterating subsidy size until targets in each region met. three scenarios compared to reference scenario in which no growth of biofuels.	Biofuels developments in USA, EU and Brazil combined will have significant impact on world agricultural prices and production levels, particularly in feedstock crops (maize, oil crops, sugar and cassava). Additional impact of GMS regional biofuels developments revealed to have "little impacts" (ibid, p. S45) on global agricultural prices or production.	Increasing the price of land, this will raise the price of other crops, causing "moderate" declines in their production. Rural land owners and food producers estimated to see increases in incomes, while net food purchasing poor expected to be damaged by global biofuels development.

	Paper	*Region(s)*	*Static/ dynamic*	*Treatment of land*	*Approach to incorporating biofuels technologies*	*How are shocks modelled?*	*Results (jobs, GDP)*	*Importance of land constraint (if used)*
14	AL-RIFFAI *et al* (2010)	Global, with results presented at 11 regions disaggregation.	Recursive dynamic	Land is distinguished by agro-environmental zones, allowing crop substitution with land use unchanged in aggregate, and expansion of arable land for cultivation. Land substitutes with "natural resources", "labour" and "capital/energy" composite in the production of "value added and energy".	GTAP database for 2004 disaggregated with 23 new sectors representing liquid biofuels sectors (*incl*. ethanol and biodiesel), major feedstocks, co-and by-products, fertilizer sector and transport fuels sector.	Baseline scenario with US and Brazilian targets implemented for 2020, along with targets for Indonesia, Malaysia, Rest of the OECD and China. EU biofuels remain at current levels in "baseline". Central scenario in which EU mandate increases to 5.6% of fuels from renewable at future fuel usage, but all else remains unchanged. Sensitivity scenarios with EU 5.6% target and alternative trade policy assumptions – 1) business as usual trade policy, 2) full, multilateral biofuels trade liberalisation, 3) EU bilateral trade liberalisation with MERCOSUR (Argentina, Brazil, Paraguay and Uruguay).	Required biodiesel production largely comes from EU, while bioethanol mandate increases demand for Brazilian bioethanol. Real income rises in Brazil and EU, but slightly reduced elsewhere. Global cropland increases by 0.07%, "showing that there is indeed indirect land use change associated with the EU biofuels mandate" (*ibid*, p. 12). Crop land increases by +0.54% in central case in Brazil, principally drawn from savannah/grassland. Limited effects on world food prices, but these do increase. Indirect land use changes increased in full liberalisation scenarios as land use increases outside the EU (but environmental good as this (Brazilian ethanol, largely) has lower emissions intensity than EU biodiesel).	"Analysis of the indirect land use change effects by crop indicates that ethanol, and particularly sugar-based ethanol, will generate the highest potential gains in terms of net emissions savings" (AL-RIFFAI *et al*, 2010, p. 12).
15	TRINK *et al* (2010)	"Two-plus-ten" model of East Styria, rest of Styria (both regions of Austria) and ten other regions representing the world.	Comparative static	Cultivated land is available for use by all sectors and substitutes for Labour-Capital-Energy composite in production function with elasticity of 0.1. Capital and land assumed to be fully employed in each region. Real wage fixed in each region.	GTAP database for the world disaggregated to capture East Styria and the rest of Styria and the rest of the world major economic regions. Biodiesel is incorporated through disaggregating the production and use of rapeseed methylester (RME) for substitution for existing diesel use.	Development of biomass sector in East Styria (region 1) stimulated to increase the rate of biodiesel produced to 5.75%, 10% and 20% of diesel consumed.	Increasing the share of diesel from biodiesel and the "import share" (the amount of biomass feedstock imported into region 1) have positive impacts on region 1 GDP and employment. For instance, higher shares of biofuels feedstock importing, for a given biodiesel production level, produces more positive changes in GDP and employment (but negative in lowest import share cases). "Long-run" scenario used for domestic prices matching international prices, and in all scenarios biofuels produce negative effects on GDP and employment of region 1.	When accounting for land competition "a significant increase in land rent occurs when agricultural land is used for producing biomass". As this crowds out traditional (and more labour intensive) farming, the net employment impacts turns negative for those pre-energy biomass products that are land intensive" (TRINK *et al*, 2010, p. 13)

ENDNOTES

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[1] This includes electricity or hydrogen from renewable energy sources.

[2] By their estimates, renewable energy from biomass was responsible for employment of over 1.1 million in 2006. Primarily these jobs were in Brazil, the United States and China.

[3] In this paper, when discussing the impact of biofuels development on the regional or local economy, we use the terms local and regional interchangeably to refer to the economic area within which the biofuels facility is located.

[4] Other modelling approaches, including SASTRESA *et al* (2010) and MORENO and LÓPEZ (2008) have the direct impacts of renewable energy technologies, but not the (potentially significant) impact across the regional economy.

[5] "Final demand" categories include purchases of each sector's output by households, government and other components of consumption, including capital formation, stocks, and exports from the region. Exogenous final demands for the output of production sectors are given in matrix F_1.

[6] For a detailed derivation of the Leontief inverse see MILLER and BLAIR (2009, p. 15-21).

[7] Under Type 1 a change in exogenous final demand for a sector's output would cause knock-on ("indirect") effects on other intermediate industries from which this sector (and those linked to the stimulated sector) purchased inputs. Under a Type 2 configuration, increased household income and expenditure is incorporated, causing a further ("induced") economic impact. The effect of the exogenous demand disturbance would therefore be greater than the initial change in exogenous demand under both Type 1 and Type 2 closures, with the scale of the aggregate impact to the initial disturbance referred to as a "multiplier".

[8] If there are two factor payments (e.g. wages and other value added) and three institutions (households, corporations and government) this is a 3x2 matrix where element $v_{i,j}$ is the payment from factor income i to institution j.

[9] An alternative interpretation might be that whilst technical substitution is possible, input prices do not change as a result of the demand stimulus to the sector, so that the cost-minimising production technique is unaffected by the scale of output (MCGREGOR *et al*, 1996).

[10] Readers will note that these assumptions are inter-related, e.g. one interpretation of the fixed coefficient assumption in an IO context is that supply is entirely passive, and so output can increase without any impact on relative prices.

[11] VARGAS *et al* (1999) summarise CGE modelling methods for the regional economy, while PARTRIDGE and RICKMAN (1998; 2010) review the application of CGE methods to regional economic development analysis.

[12] Unlike IO or SAM modelling, the CGE modeller has more discretion over the specific nature of production, consumption and trade relationships.

[13] Such changes could be reflected in adjustments to the A matrix.

[14] We ignore studies done by consultancies (e.g. URBANCHUCK, 2007; 2010):

[15] Papers by CUNHA and SCARAMUCCI (2006), HODUR and LEISTRITZ (2008) and FERNANDEZ-TIRADO and PARRA-LOPEZ (2010) appear to make no specific adjustments to modelled results.

[16] THOMASSIN and BAKER (2000) do two alternatives to their "unconstrained" scenario (i.e. without a demand offset). In one of these there is a reduction in the demand of the output of the gasoline sector. The second alternative case they examine assumes that there is some reduction in the final consumption of corn (e.g. such that the corn sector does not expand by the full amount suggested by an unconstrained IO application. This is similar to the third adjustment approach we identify.

[17] Papers which do not focus on biofuels, but on the production of electricity from bioenergy crops have been omitted from this analysis (e.g. SCARAMUCCI *et al*, 2006; IGNACIUK and DELLINK, 2006; WIANWIWAT and ASAFU-ADJAYE, 2011). Also excluded are papers which only used partial equilibrium models (e.g. FONSECA *et al*, 2010), or that focus only on the agricultural sector (e.g. SCHNEIDER and MCCARL, 2003).

[18] Appendix A gives the details of fifteen global studies which have used CGE models to examine the impact of biofuels production.

[19] Marine algae for biofuels production could, however, displace existing economic uses of the marine environment.