INTRODUCTION

The cultivation of biomass to produce biofuels can indirectly cause additional deforestation and land conversion. When existing agricultural land is turned over to biofuel production, agriculture might expand elsewhere to meet demand for food, feed and materials. If this expansion happens at the expense of carbon-rich or highly biodiverse ecosystems, it can substantially affect the benefits of substituting fossil fuels with biofuels. Therefore, an accurate measure of the sustainability of biofuels must account for the direct and indirect effects on the use of land resources.

Over the past decade, many approaches have been developed to estimate the Indirect Land Use Changes (ILUC)
of biofuels (Geert et al., 2017; Panichelli & Gnansounou, 2015; Wicke, Verweij, Meijl, Vuuren, & Faaij, 2012). However, the assessment of ILUC remains a challenging task with studies displaying a wide variability of estimates due to differences in modelling approaches, input data, parameterization, scenario assumptions and spatial coverage (Ahlgren & Di Lucia, 2014; Geert et al., 2017; Marelli, Mulligan, & Edwards, 2011; Wicke et al., 2012). Large uncertainties about facts and/or causal relationships have hindered the credibility of these modelling efforts with the effect of undermining public policy and business decisions. In this study, we suggest that these limitations can be addressed by adopting a project level approach to ILUC assessment, in contrast to the view that ILUC of biofuel is a global phenomenon which cannot be linked to specific activities and is, thus, largely outside the control of producers. By focusing our attention on the analysis of individual projects, embracing the social context of the changes, we can provide a richer understanding of the contextual conditions that affect land use change dynamics.

The viability of a project level assessment of ILUC is possible in the context of projects where the origin of the biomass feedstock can be traced to a specific location as is often the case with advanced biofuel technologies. Projects employing these technologies rely on waste and residues, which are often uneconomic to transport for long distances, or dedicated energy crops, which are not global commodities, but tend to be locally supplied for economic, environmental and political reasons. In these instances, the largest share of the direct land-based effects occurs within a geographically defined area, while the direct effects mediated by global markets are expected to account for a relatively small share of the total effects.

In this paper, we present and evaluate an empirically evidenced causal-descriptive approach—ILUC Project ASsessment Tool (ILUC PAST), designed to assess the direct and ILUC effects of individual biofuel projects. The approach relies on a multistep, multitool analysis combined with extensive engagement of local actors to provide (a) quantitative estimates of the direct and indirect LUC generated by the project and (b) an in-depth understanding of the cause-and-effect dynamics that generate those effects. The ambition of ILUC PAST is to provide knowledge of land use dynamics that is of a sufficient quality to support effective decision-making. This is advanced by improving the assessment’s credibility and legitimacy through stakeholders’ participation.

We evaluated ILUC PAST on a real-world project for the production of advanced ethanol in Sardinia (Italy). The project was selected for its focus on nonfood biomass feedstock and local supply chains, and for the availability of detailed information of the project’s design. The results of the case study were used to benchmark ILUC PAST against two alternative approaches for project level assessment: (a) ‘Low Indirect Impact Biofuel’ (LIIB; RSB, 2015); and (b) ‘iLUC Club’ (Schmidt, Weidema, & Brandão, 2015).

2 | PROJECT LEVEL ASSESSMENT OF ILUC OF BIOFUELS

Due to its indirect nature, ILUC is a not a phenomenon that can be directly observed and measured in a given place and time. To overcome this, studies have applied various approaches to model and simulate ILUC with most biofuel-related approaches falling into two broad categories: Economic Equilibrium Models (EEM) and Descriptive Models (DM). Several studies have analysed and compared the strengths and weakness of these approaches, and the uncertainty linked to their estimates (see e.g. Geert et al., 2017; Marelli et al., 2011; Panichelli & Gnansounou, 2015; Wicke et al., 2012).

Economic Equilibrium Models attempt to evaluate the effects of increasing biomass demand by modelling the whole economy (general equilibrium models), or a sector of the economy (partial equilibrium models) based on the concept of economic equilibrium where supply and demand are equilibrated through price adjustments (Geert et al., 2017). In order to estimate LUC, EEM models consider an initial baseline scenario and a future scenario with additional demand for biofuel, normally referred to as ‘biofuel shock scenario’ (Edwards, Mulligan, & Marelli, 2010). The difference between the two scenarios represents the effects of increasing biofuel demand on global commodity markets from which the impact on land resources can be calculated. Although widely applied, EEM are subject to important limitations which hinder their application to decision-making. In particular, the value of EEM is hindered by the high variability of results, a consequence of the large uncertainties affecting assumptions on key parameters, but also by the low traceability, transparency and accessibility of the models, as well as the low applicability to new supply chains (Geert et al., 2017). EEM tend to be applied at national, multinational, or global level (generally with one demand country and several supply countries) due to their complexity and computational intensity (De La Rosa, Schmidt, Knudsen, & Hermansen, 2014; Geert et al., 2017; Panichelli & Gnansounou, 2015). As a consequence, these models are poorly suited to reflect local conditions in relation to, for example, local land use patterns, specific carbon stocks, land tenure and ownership systems, management practices and societal preferences (Dunkelberg, 2014).

Along with the adaptation and use of EEM, several DM have been developed to study the ILUC of biofuels. Rather than the complex optimization methods applied by EEM, these DM models use descriptive methods to set criteria that attribute responsibility for land conversion under the assumption that past patterns of land use are an adequate
proxy to estimate global averages of potential ILUC (Geert et al., 2017). DM are praised for providing an understanding of the macro picture of the LUC induced by biofuel production (Panichelli & Gnasounou, 2015) and for being more transparent than EEM (Dunkelberg, 2014). However, they may miss important details with respect to the complex market feedbacks and endogenous crop yield intensification processes (Wicke et al., 2012). Regarding the scale of application, even though DM are more suitable to capture the cause–effect relationships for small-scale applications (De La Rosa et al., 2014), their ability to consider regionally specific characteristics is still limited (Dunkelberg, 2014). Finally, similarly to EEM, DM have been generally applied to assess policy scenarios and not individual biofuel projects.

Due to the limitations of EEM and DM, a third alternative approach has emerged in the past years. Instead of attempting to estimate ILUC, this approach seeks to identify ‘Low ILUC risk’ biofuels, that is, biofuels produced from feedstock which have a low chance of displacing other land-based activities (Peters et al., 2016; Wicke, Brinkman, Gerssen-Gondelach, Laan, & Faaij, 2015). The rationale here is to avoid situations that can lead to ILUC recognizing that the uncertainties affecting current ILUC quantifications cannot be eliminated. This idea was developed by the ILUC-Prevention Project (Wicke et al., 2015) into a method to evaluate the risk of ILUC and provide measures to mitigate such risk in specific locations. The method has been successfully applied to assess biofuel production at regional level for example, in Hungary (Brinkman, Wicke, & Faaij, 2017), Poland (Gerssen-Gondelach, Wicke, Borzęcka-Walker, Pudełko, & Faaij, 2016), Indonesia (Van der Laan, Wicke, Verweij, & Faaij, 2017) and Romania (Brinkman, Hilst, Faaij, & Wicke, 2018). A similar method based on the low-ILUC risk idea is the ‘LIIBs’ methodology (RSB, 2015) which consists of a set of criteria and indicators for economic operators to demonstrate that their operations have a low risk of ILUC. The LIIB methodology has been tested on pilot cases for example, in Brazil (integration of sugarcane and cattle production), Mozambique (cultivation of unused land), South Africa (residue and waste) and Indonesia (yield increase of palm oil; Van de Staaaij et al., 2012). These case studies demonstrated that the low ILUC risk approach is applicable at regional and local scale, and can contribute to the design of mitigation strategies without being able to provide quantitative estimates of ILUC.

Our review of the literature confirmed that the quantification of ILUC at project level has received limited attention and has largely been considered impractical, time consuming and/or not possible (Van de Staaaij et al., 2012). We identified only a few studies in which the ILUC of biofuel were assessed at local scale (Affuso & Hite, 2013; Dunkelberg, 2014; Silalertruksa, Gheewala, & Sagisaka, 2009; Tonini, Hamelin, & Astrup, 2016) and only one commercially available approach, ‘iLUC Club’ developed by Schmidt et al. (2015), potentially suitable, but still untested, for project level assessment (J. Schmidt, Personnel Communication, April 26, 2018).

3 | THE ILUC PAST FRAMEWORK

The ILUC PAST presented in this paper is an empirical causal descriptive approach that establishes a robust cause-and-effect framework to connect biofuel supply chains with changes of land use and management allowing both direct and indirect effects to be quantified. The framework relies on (a) a tiered process where impacts are estimated in a stepwise process from local to global, (b) a multistep analysis including spatial analysis, System Dynamics (SD) modelling, statistical and market data analysis; and (c) an intense process of engagement of local stakeholders and experts. The validity of each component of the analysis including input data, model assumptions and model results, is evaluated throughout the life cycle of the assessment via participatory processes.

An overview of the ILUC PAST is provided in this section (Figure 1), while further details are available in the online Supporting information (Section S1).

STEP 1 of ILUC PAST focuses on the definition and characterization of the biofuel supply chain(s) to be assessed. To maximize the value of the assessment, supply chains should be defined based on real world rather than hypothetical configurations. For that reason, the business plan of the target project should be used as a starting point to characterize each supply chain. This process includes the delimitation of the geographical scope of the supply chain, which could rely on biomass sourced from (a) the area surrounding the conversion unit, that is, biomass catchment area; (b) areas geographically disconnected from the catchment area, for example, neighbouring countries or regions; and (c) undefined locations or global commodity markets. Each option is analysed respectively in STEP 2, STEP 3 and STEP 4.

STEP 2 assesses the effects of the supply chain within the biomass catchment area applying a five-stage process:

- In stage 2.1, the geographical boundaries of the catchment area are delineated, and the area is characterized. Geographic Information System (GIS) data and techniques are applied to provide a detailed, spatially explicit inventory of the physical, natural and socio-economic assets of the area. This inventory is of key importance for the following stages.
- In stage 2.2, the theoretical potentials of the catchment area for land and/or biomass production are quantified and spatially delineated. These potentials represent the quantity of land and/or biomass resources existing in the area...
in compliance with the project requirements considering biophysical features and socio-economic factors, but without accounting for existing uses. Spatial Multi-Criteria Analysis (SMCA) is a suitable approach to develop spatially explicit datasets of resource potentials (Fiorese & Guariso, 2010; Lewis & Kelly, 2014; Pulighe et al., 2016). These data sets provide critical knowledge to estimate the effects of the project in the catchment area in stage 2.5.

- Stage 2.3 evaluates the competitive uses of the theoretical potentials. Through market analysis and expert consultation, this stage seeks to quantify the uses of resources and understand how uses are affected by local conditions (e.g. cultural, economic, environmental, political, etc.). The analysis results in quantitative estimates of utilised potentials, that is, resources already required by pre-existing productive activities, and unutilised potentials, that is, resources not dedicated to productive activities.

- In stage 2.4, the amount of biomass feedstock required by the biofuel project is converted into hectares of land, or tons of local biomass. In this process, detailed knowledge of the local conditions affecting biomass productivity and the type and quality of biomass feedstock available in the catchment area are used to estimate the project's demand of land-based resources. The analysis provides a set of scenarios of land, or biomass demand which are used to simulate direct and indirect effects in stage 2.5.

- Stage 2.5 estimates the direct and indirect effects of the biofuel supply chain. Employing the results of stages 1–4, it provides quantitative estimates of direct LUC and potential displacement effects caused by competition with current land uses. For this purpose, SD modelling is applied in this stage for visual representation of the feedback structures of the dynamic system and to conduct simulations, sensitivity analysis and scenario explorations (Sterman, 2001). SD models have been used to simulate the impact of biofuel production on LUCs (see e.g. He et al., 2005; Warner et al., 2013). The modelling results show the extent to which the biofuel supply chain generates (a) no LUC; (b) DLUC but no displacement effects; and (c) DLUC and ILUC due to resource competition. In the event of land use displacements (c), this stage seeks to establish the geographical scope of such effects. Effects which can be allocated with a sufficient level of confidence to known locations are assessed in STEP 3, while all other ILUC are evaluated in STEP 4.

The quality and value of the results of ILUC PAST are enhanced through an iterative process of validation performed after each stage in STEP 2 (details provided in Section S1 of Supporting information). The validation seeks to make visible key uncertainties affecting the analysis including input data, model assumptions, causal relations and modelling results. The goal is to provide knowledge of a sufficient quality for decision-making by exposing these uncertainties through participatory forms of sensitivity analysis (Saltelli & Funtowicz, 2014) and scenario analysis (Oteros-Rozas, Ravera, & Palomo, 2015).
STEP 3 assesses the displacement effects occurring in known locations, as identified in stage 2.5, and the supply chain effects emerging from STEP 1 (Figure 1). This analysis compares biofuel demand for land/biomass against available resources calculated as the difference between theoretical potentials and current uses. The depth of this analysis is limited by the use of (a) low-resolution data at country or regional level; (b) nonspatial data; and (c) the lack of participatory activities. For these reasons, the results of this third step should be interpreted in a conservative way when drawing conclusions. If further displacement of productive uses cannot be excluded, the effects are assessed in STEP 4.

In STEP 4 all the effects not linked to specific geographical areas are evaluated. These effects include (a) the effects of global supply chains as identified in STEP 1; (b) the displacement of productive activities from the catchment area from STEP 2; and (c) the further displacement of productive activities from STEP 3 (Figure 1). The quantification of these effects can be conducted employing the results of one or more generalized global models selected considering, in particular, the specific features of the supply chain assessed including the biomass type and land conversion, the time period covered, the policy scenario considered and other basic assumptions. However, cases which generate a substantial impact in unknown locations, or on global markets should not be analysed employing ILUC PAST methodology.

4 | APPLICATION OF ILUC PAST TO A PROJECT FOR ADVANCED ETHANOL PRODUCTION

In this section, we illustrate the practical application of ILUC PAST to a project for commercial scale production of cellulosic ethanol from dedicated crops initiated in 2012 by Biochemtex, an Italian biofuel technology developer, on the Italian island of Sardinia (for details of the project see Di Lucia, Usai, & Woods, 2018).

4.1 | STEP 1: Definition of the biofuel supply chain

The business plan of the project identified the municipality of Portovesme, in the south-west of Sardinia (Figure 2), for the location of the industrial site, and Giant Reed (*Arundo donax*) as the dedicated biofuel feedstock. Local field trials showed that due to favourable agronomic and climatic conditions in Sardinia, with appropriate management practices Giant Reed could provide high biomass yields, in the range of 25–35 tDM/ha (Arca, 2017). Importantly, all the Giant Reed required by the project was to be supplied from an area of 75 km maximum distance from the conversion plant. The key details of the Giant Reed supply chain are summarized in Table 1.

4.2 | STEP 2: Assessment of the effects within the biomass catchment area

The catchment area was delineated and characterized by developing a spatially explicit inventory of the physical, natural and socio-economic assets (stage 2.1). In the process, the geographical boundaries of the area were drawn up considering the location of the industrial plant and a 75-km buffer area (Figure 2).

The characterization of the catchment was developed building on the IULC data set reported in Di Lucia et al. (2018) (Figure 3). The process followed to produce this data set is illustrated in the Supporting information (Section S2). However, the modifications required by differences in the temporal coverage of the two studies are illustrated here. In the process, the original data set was compared against agricultural land use statistics from the National Office of

![FIGURE 2 Biomass catchment area of the biofuel project](image)
Statistics (ISTAT) for the year 2015 (ISTAT, 2018). From this exercise, it emerged that, with the exception of pastureland, most land uses suffered only minor changes over the period 2013–2015. Pastureland decreased by c. 45,000 ha, or 20% of total pasture in 2013, due to a controversial process at EU level—‘EU CAP refreshment’, in which pasture considered not sufficiently managed by farmers was reclassified into natural areas (AGEA, 2016). The outputs of this exercise were reviewed in meetings with experts of the Regional Agency for Agriculture, regional farmers’ associations, local universities and research institutes. These actors confirmed that pastureland areas reclassified in 2013 were still largely used for grazing in 2015. For this reason, the original data set from Di Lucia et al. (2018) was revised to match ISTAT (2018) statistics with the exception of pastureland, which was kept at pre-EU Refreshment levels. The uncertainties connected to the quantification of pastureland were explored via sensitivity analysis in stage 2.5.

In stage 2.2, the theoretical potentials of the catchment area, that is, land suitable for Giant Reed cultivation, were assessed applying SMCA based on a GIS overlay process with binary evaluation (see Pulighe et al., 2016) and utilizing the environmental, topographic, agronomic and techno-economic criteria identified in STEP 1. In the process, we selected pasture areas in the spatial data set of land use/cover, before we removed land of medium-low quality (classes V and above from the regional map of land capability (RegSard, 2018)), areas with slope >8% (Digital Elevation Model of the Sardinia region (RegSard, 2018)) and parcels with an area <0.5 ha. The results showed that of the c. 218,000 ha of pastureland existing in the area, c. 83,000 ha were suitable for Giant Reed cultivation in compliance with the project requirements. The validity of both the input data and the results of this analysis was reviewed with representatives of the Regional Agency for Agriculture and the local experts involved with the Giant Reed field trials (Arca, 2017).

In the following stage (2.3), the current uses of the theoretical land potentials were investigated. The ambition of this exercise was to understand under what conditions the biofuel supply chain generates competition for land resources and, thus, the displacement of productive activities. For this purpose, we identified the sheep farming sector as the main user of pastureland in the catchment area. Consultations with local farmers and experts provided two key pieces of information not otherwise available in the literature: (a) feed practices in local sheep farming consist of a combination of grazing and feedlots; and (b) grazing is usually carried out daily for 4–6 hr in areas within a maximum distance of c. 1.5 km from the

| TABLE 1 Characterization of the Giant Reed supply chain |
|---------------------------------|-----------------|
| Plant output capacity           | 80,000 t/yr     |
| Biomass feedstock               | Giant Reed (Arundo donax) |
| Plant feedstock capacity        | 432,000 tDM/yr  |
| Land requirements for           |                 |
| Giant Reed cultivation          |                 |
| Pastureland                     |                 |
| Medium/high quality land        |                 |
| Slope <8%                       |                 |
| Within 75 km from conversion unit |               |
| Land parcels >0.5 ha            |                 |
| Irrigated or rain fed cultivation|                 |

FIGURE 3 Land use/cover status of the biofuel catchment area: (a) in 2013 (Di Lucia et al., 2018); (b) in 2015 (based on a modified version of a)
farm stables. This understanding was instrumental for the quantification and spatial delineation of unutilised pastureland. In the process, we used data on the location and livestock volumes of each of the c. 4,000 farms existing in the area to delineate the unutilised pastureland (c. 35,000 ha) and the share considered suitable for Giant Reed cultivation in line with the project requirements from STEP 1 (c. 3,800 ha).

By default, the remaining pastureland (c. 183,000 ha) was considered utilized by sheep farmers. However, local experts and farmers suggested that these areas were often only partly utilized since farmers tend to maintain agricultural land as pasture even when these areas are not needed to sustain their livestock. Armed with this knowledge, we estimated the land needed to sustain the existing sheep population—allocated pastureland, and the land not required—unallocated pastureland. In the process, we calculated each farms' carrying capacity as the difference between the supply and demand of biomass from grazing. First, the supply of biomass was modelled as a function of the productivity of pastureland applying a set of yields developed in collaboration with local agricultural and animal farming experts. Biomass yields were spatially assigned based on land capability classes, slope and management practices, that is, irrigation. Second, the demand of biomass was estimated considering animal densities and average intake of grazed biomass at farm level. The results of this analysis showed a total supply of biomass for grazing of c. 453,000 tDM/year against a demand of c. 363,000 tDM/year in the area (details in Section S3.1 of Supporting information).

From these results, and assuming no changes in land management, that is, maintaining pastureland yields constant, we estimated the amount of pasture unallocated (c. 55,000 ha) and pasture allocated to sheep farming (c. 129,000 ha).

In stage 2.4, the land requirements of the biofuel project were calculated based on a total demand of biomass feedstock of 432,000 tDM/year at plant full capacity, and the biomass yields of Giant Reed from local field trials (Arca, 2017). In the process, yields were spatially assigned based on land capability classes and irrigation practices to estimate average yields for the entire catchment. Average yields for the catchment area were c. 15 tDM/ha under a Rain fed scenario and c. 25 tDM/ha under an Irrigated scenario in which all areas serviced by the irrigation network are irrigated. As a result, between 17,300 ha (Irrigated scenario) and 28,900 ha (Rain fed scenario) of Giant Reed were required to supply all the biomass feedstock required by the biofuel project.

Finally, stage 2.5 addressed the effects of the Giant Reed supply chain on land use dynamics in the catchment area with the help of a SD model. In the following, we present the main results and some of the critical issues identified in SD modelling exercise (for further details see Di Lucia et al., Forthcoming).

The structure of the SD model, illustrated in Figure 4, prioritizes the conversion of unutilized and unallocated pastureland to Giant Reed before allocated pastureland is affected. The conversion of allocated pasture reduces the capacity of the catchment area to sustain the sheep population and this, in turn, results in lower production of milk and, thus, cheese. At the same time, due to a rather inelastic demand of sheep cheese from Sardinia, a decrease in cheese supply results in higher cheese and, thus, milk prices. Note here that milk prices are the main reference point for farmers seeking to manage the size of their flocks. This process is implemented in the SD model by identifying as a tipping point the economic break-even point for milk production of a typical farm in the area (0.75 €/L; AGRIS, 2017). Prices below this point lead farmers to reduce the number of animals, while prices above this value result in an increase. In the latter case, the biomass required for feeding is provided.
by expanding grazing into unallocated pastureland, or increasing the use of forage in the feed ratio since the conversion of food cropland was considered by local experts as ‘unlikely under current market conditions’. The unmet demand for sheep cheese generates the displacement of sheep farming activities to areas outside the catchment area.

The results of the modelling exercise showed that the conversion of pastureland to Giant Reed causes the conversion of unutilized and unallocated pasture under either crop management scenarios without causing competition for land resources with the sheep farming sector (Figure 5).

The SD model and the simulation results were reviewed with local stakeholders and experts in a workshop setting (see Di Lucia et al., Forthcoming for details of the workshop). Participants largely considered the assumptions and model structure, illustrated above, appropriate for the analysis and in line with their knowledge of the real system. However, they highlighted the importance of uncertainties concerning natural variations of agricultural yields, sheep productivity and in particular, pastureland availability in the catchment area. While these uncertainties were all explored with the SD model through sensitivity analysis (Di Lucia et al., Forthcoming), the availability of pastureland emerged as a key factor. For this reason, we simulated different ranges of available pastureland in the catchment area by subtracting up to 45,000 ha, or 100%, of the EU CAP Refreshment. To notice here that due to the limitations of the land data available we could not spatially allocate the land affected by the exercise. Therefore, we considered that the EU CAP Refreshment did not affect unutilized pastureland. The results showed that under the most conservative configuration, that is, when total pastureland is reduced by 45,000 ha (right-hand figures in Figure 5), the Giant Reed supply chain results in the conversion of between 4,000 ha (Irrigated scenario) and 16,000 ha (Rain fed scenario) of allocated pasture. As a consequence, the SD model estimated the displacement of sheep farming activities responsible for the production of between c. 2.5 and c. 10 million litres of milk per year.

The last part of stage 2.5 focused on the definition of the geographical scope of the potential displacement effects of the land constrained configurations. Relying on a review of the literature on sheep farming, an analysis of market trends and consultations with sheep farming experts in Sardinia, we identified five alternative scenarios. Four scenarios entailed the displacement of sheep farming to (1) the rest of the island; (2) the rest of Italy; (3) Spain; or (4) countries in east Europe. One scenario (5) consisted of a reduction in the international demand for Sardinian sheep cheese due to higher cheese

![Figure 5](image-url)

**Figure 5** Impact of the Giant Reed supply chain on pastureland in the catchment area. Notes: Results of the simulations of the System Dynamics model for the Irrigated and Rain fed scenarios under unconstrained and constrained conditions of pastureland availability. Pasture conversion to Giant Reed occurs at year 2 of the simulation.
prices in the catchment area. Each scenario was reviewed with local experts. Scenario (1)—the displacement of sheep farming activities to the rest of the island, was identified as the most likely scenario under current market and biophysical conditions since the sheep cheese sector in Sardinia works at regional scale featuring one price of milk and only a handful of large cheese producers for export. Scenarios (2) to (4) were considered plausible, but less likely, that is, displacement would affect these areas only for the effects not absorbed by the rest of the island. Scenario (5) was debated considering questions such as the elasticity of the (international) demand of sheep cheese, Sardinia is the largest and cheapest supplier of this type of cheese in the US market. Having identified with a sufficient level of confidence, the geographical scope of the displacement effects, the assessment moved to STEP 3.

4.3 | STEP 3: Assessment of the effects in the rest of the island

The analysis of the effects in the rest of the Sardinian island was conducted as a desk-based study. The geographical boundaries of the study area were delineated by considering the total area of the island with the exception of the 75 km buffer area. The study area was then characterized employing only official statistics from ISTAT for the year 2015 without considering the uncertainties affecting these data, in particular, with regard to the size of the pastureland. Employing these data and official livestock data from ISTAT (2018), we estimated the demand and supply of pastureland for sheep farming. The results showed that pastureland in the rest of the island was largely underutilized with only 75% of the existing c. 720,000 ha allocated to sheep farming, while the remaining c. 180,000 ha of pasture was unallocated. This area was compared against the area required to absorb the displacement effects identified in STEP 2 for the most conservative land constrained configurations. The additional production of between c. 2.5 and c. 10 million litres of milk per year in the rest of the island could require an increase in the sheep population between c. 120,000 heads (Rain fed scenario) and c. 50,000 heads—(Irrigated scenario) and an expansion of pastureland allocated to sheep farming between c. 24,000 (rain fed) and 11,000 ha (irrigated). At the end of a period, roughly 10 years, the island of Sardinia has more sheep and more pastureland allocated to sheep farming under these two Giant Reed scenarios compared to a scenario without biofuel. This is caused by lower levels of milk and pasture productivity in the rest of the island compared to those in the catchment area where the direct impacts occur (AGRIS, 2017).

4.4 | STEP 4: Assessment of effects in unknown locations

In the case study, STEP 4 was not required because there was no evidence of direct effects caused by the biofuel project via global supply chains (STEP 1) or displacement effects to unknown areas from either the catchment area (STEP 2), or the rest of the island (STEP 3; Figure 1).

5 | RESULTS OF THE CASE STUDY

The application of the ILUC PAST provided quantitative estimates of direct and indirect LUC, and a qualitative understanding of the causal chains which cause LUC in the case study.

The quantitative results showed in Figure 6 suggest that all the Giant Reed required by the biofuel project can be produced on unutilized and unallocated pastureland within the catchment area resulting in DLUC between 17,300 and 28,900 ha, depending on the type of crop management applied, that is, irrigated or rain fed. With regard to the type of LUC, the analysis suggested that when only unutilized and unallocated pastureland is directly affected, no displacement of productive activities is caused. However, important uncertainties around data inputs emerged in the participatory validation process. These uncertainties were explored through sensitivity analysis, which showed that under the most land constrained assumptions 29% (4,000 ha)—Irrigated scenario, and 55% (16,000 ha)—Rain fed scenario, of the Giant Reed supply chain relies on pastureland allocated to sheep farming. Under these conservative conditions, the biofuel project causes the displacement of sheep farming activities responsible for the provision of between 2.5 and 10 million litres of milk per year. The consequential effects are expected to occur in the rest of the island and consist in a larger sheep population of between c. 50,000 and c. 120,000 sheep, and a change of pastureland use from nongrazed to grazed of c. 11,000 ha for the Irrigated and c. 24,000 ha for the Rain fed scenario.

The ILUC PAST also provided qualitative results in the form of insights into the cause-and-effect chains that lead to changes in the use and management of land resources. These causal effects unfold differently depending on the original type of land use affected. The conversion of unutilised pastureland generates only DLUC in the form of transformation of nongrazed pastureland to Giant Reed land. The size and dynamics affecting this type of LUC are considered steady over the period analysed due to the internal dynamics of the sheep farming sector, which has been stable over the past two decades (ISTAT, 2018). In the absence of the biofuel project, these areas are expected to remain as pastureland in order to receive the substantial farm subsidies of the EU CAP. Similarly, the conversion of unallocated pasture to Giant Reed does not generate competition with sheep farming. The size of this LUC changes over time due to the marginal status of unallocated land, that is, areas maintained as pasture to be
brought into production when market conditions allow it. Finally, the conversion to Giant Reed of allocated pasture generates both direct and indirect LUC. These emerge from feedback-rich chains of cause-and-effect in which the dynamics of the sheep sector plays a major role for determining the overall system behaviours. In Sardinia, cheese demand, especially from outside the island, determines the price of milk and, ultimately, the allocation of land to sheep grazing. In this system, an abrupt shortage of grazing land, for example, due to the introduction of Giant Reed for biofuel, causes a reduction of milk and cheese deliveries unless the loss of grazing area is compensated by an increased use of forage in the feed ratio, or higher milk productivity. Constant demand matched by lower deliveries pushes the price of milk upwards. The market reaction induces farmers in the rest of the island to expand their flocks to supply the unmet demand bringing into use some of the available resources of unallocated pasture.

6 | ALTERNATIVE METHODOLOGIES

To benchmark the ILUC PAST results, the Sardinian case study was analysed employing two alternative approaches, introduced in Section 22: the LIIB methodology and the iLUC Club. Here, we illustrate the results obtained in comparison with the results of the ILUC PAST, while further details are available in Supporting information (Sections S4 and S5).

6.1 | LIIB methodology

Low Indirect Impact Biofuel consists of a set of criteria and indicators to distinguish feedstock with a low risk of generating ILUC without having to quantify the potential ILUC (RSB, 2015). The overall principle of ‘low ILUC risk’ is to produce feedstock without displacing existing productive functions, or provisioning services of the land (Van de Staaij et al., 2012). Following this line of thinking, the methodology considers eligible feedstock grown on unused land, feedstock sourced from yield increases above business-as-usual, and feedstock classified as waste and residues (RSB, 2015). The primary use of the methodology is as a component of voluntary certification schemes, such as the Round Table on Sustainable Biomaterials, in which the LUC assessment's results are typically validated by an external certification body during an audit (RSB, 2015). For each category, the LIIB provides a range of methods suitable to demonstrate compliance (e.g. interviews with landowners, satellite images, etc.).

With regard to the analysis of the case of Giant Reed ethanol in Sardinia, the LIIB establishes criteria and indicators to demonstrate the low ILUC risk of dedicated energy crops cultivated on unused land. To be eligible, the cultivation of Giant Reed needs to occur either on ‘land not used’, or on ‘land with limited use’ for provisioning services in the 3 years.
prior to the conversion (RSB, 2015). In particular, ‘land with limited use’ is defined as land providing less than 25% of the earnings, or yields, reasonably expected from the cultivation of the same crop in normal conditions (RSB, 2015). The application of the LIIB criteria to the case study showed that only c. 14% of the Giant Reed feedstock can be considered of low ILUC risk because sourced from land not used, while the remaining c. 86% has a high risk because grown on land with limited use but not in compliance with the 25% threshold (details available in Section S4, Supporting information). For the calculations, we considered average earnings from milk sales of between 315 and 383 €/ha (based on milk market prices and pastureland yields for the area) and expected earnings from Giant Reed sales of between 600 €/ha (rain fed) and 1,000 €/ha (irrigated; calculated based on the prices offered by the biofuel project and average yields of Giant Reed as estimated in stage 2.4). The results of the LIIB can be compared to those from the application of ILUC PAST which showed that, depending on the scenario selected and the treatment of uncertainties, between 100% and 44% of the Giant Reed supply chain is ILUC free. The differences are due primarily to the way the two methodologies treat the conversion of unallocated pastureland, that is, ‘land with limited use’. ILUC PAST considers such conversion as ILUC-free based on a credible analysis of the chain of cause-and-effects generated. Such analysis, grounded on knowledge of the system elicited from local experts and stakeholders, justifies the different treatment of land uses (allocated and unallocated pasture) that cannot be distinguished without local knowledge. The results of ILUC PAST are more credible and accurate because based on land categories reflecting local conditions.

6.2 | iLUC Club method

iLUC Club developed by Schmidt et al. (2015) is a biophysical general model which follows the Life Cycle Assessment approach. The main assumption of the model is that land use changes are caused by changes in demand for land, therefore, the consequences of additional demand are estimated by defining the required input (capacity for biomass production based on the potential net primary production [NPP$_0$]) of the land using activities, and then modelling how this demand for capacity is met on the global market (Schmidt, 2015). To apply the model, it is necessary to know the NPP$_0$ value of the land use occupied, considering the five land categories covered in the methodology (arable land, grassland, extensive forest land, intensive forest land and barren land). Based on global NPP$_0$ values of the land category occupied and the amount of land affected, the model estimates the quantity of land necessary to compensate for the land conversion, assuming that a certain share of the effects is absorbed by land use conversions and another by intensification (Schmidt, 2015). The results in terms of land use changes (hectares and types of land use conversion) are then used to estimate the associated GHG emissions.

In the Sardinia case study, iLUC Club approach estimates that between 12,600 ha (Irrigated scenario) and 21,000 ha (Rain fed scenario) of arable land is necessary to compensate for the occupation of respectively 17,300 and 28,900 ha of pastureland. It focuses on arable land as the land type converted because, according to the model categories, grassland does not support cultivation of crops (J. Schmidt, personal communication, April 26, 2018). Since the model relies on NPP$_0$ values, it does not need to identify to what extent the occupied land is used. This assumption implies that all pastureland converted to Giant Reed is considered used, that is, no ILUC-free feedstock. Two methodological assumptions explain why less land is needed to compensate for the land directly occupied. Firstly, the method refers to NPP$_0$ values in the analysis with values selected for the study area being lower than the global average NPP$_0$ values used for the analysis. Yet, the focus on NPP$_0$ neglects the effective use of the areas affected. Secondly, the method allocates a fixed share of the compensation effect to yield increases/intensification based on global past trends even though global past trends might not be fully representative of the specific conditions in the case study area. These results can be compared with the results of ILUC PAST which showed that only under land constrained conditions (see STEP 3 in Section 44) the Giant Reed supply chains cause ILUC. The sensitivity analysis of ILUC PAST showed that under the most restrictive conditions, the project generates ILUC of c. 11,000 ha in the Irrigated scenario and c. 24,000 in the Rain fed scenario from the occupation of respectively c. 4,000 and c. 16,000 ha of allocate pasture. This analysis refutes both key assumptions considered by the iLUC Club based on evidence that the land occupied in the catchment area is more productive (tons biomass/ha) than the land converted in the rest of the island, while increases of overall milk productivity at farm level are expected to be marginal.

7 | DISCUSSION

The aim of this study was to develop a novel approach to assess the ILUC of biofuels at project level and evaluate the ability of this approach to provide knowledge of land dynamics useful to support effective decision-making. The ILUC PAST approach allows the simulation of land use dynamics caused by individual projects providing quantitative and qualitative outputs.

The quantitative estimates of direct and indirect LUC provided by ILUC PAST can be used to evaluate the overall sustainability of biofuels beyond GHG emissions. This
knowledge can be used by project developers seeking to evaluate the performance of different supply chain configurations on key indicators. The results of the case study showed that the irrigated supply chain generates c. 47% less LUC than the rain fed in the most conservative land constrained configuration. These LUCs generate emissions of GHG between 7.5 and 16.5 g CO₂ eq. per MJ of ethanol (calculations available in Section S6, Supporting information). ILUC PAST also yields information useful for local public decision makers seeking a more comprehensive view of the benefits and trade-offs of a specific project. In Sardinia, the regional government responsible for developing land use planning documents, such as the ‘Regional Landscape Plan’ (RegSard, 2004) can use this knowledge to promote the valorization of environmental resources in line with local ambitions and concerns.

The qualitative understanding of the causal chains generating changes on the use and management of land resources can be used to improve the performance of the project supply chain(s). Relying on this knowledge, project developers can design supply chains that reduce, or avoid competition with other land users. In the case study, the biofuel developer could prioritize the contracting of farmers with sufficient areas of unutilized, or unallocated pastureland, while supporting these farmers with the relocation of sheep grazing activities to areas not suitable for Giant Reed. However, in cases where the conversion of allocated pasture is required, project developers could introduce measures aiming at mitigating the impacts on sheep farming, for example, by supporting investments to increase milk yields considering that productivity varies between 96 and 215 kg per head per year in the catchment area (AGRIS, 2017). At the same time, local authorities can use this understanding of the system behaviours over time to ensure that projects are in line with local concerns and priorities. In Sardinia, the implementation of Giant Reed supply chains would leave little to no spare pastureland for a future expansion of sheep farming in the catchment area. Sheep farming is a vital element of the local economy, culture and history of the island. Considering the importance of the sector and knowing how the negative and positive effects of the biofuel project are generated, local authorities could introduce measures to mitigate the negative effects of the project, for example, by promoting investments to increase pastureland productivity in the island, supporting the production and use of forage feed, or promoting sheep species more adapted to feedlots.

Benchmarking ILUC PAST against alternative methodologies—LIIB and iLUC Club, provided insights on the current potentials and limitations of methods for project level assessment (Figure 7). The development of LIIB has been motivated by the large uncertainties affecting quantitative estimates of ILUC. To promote confidence, LIIB requires the use of context-specific data and some level of engagement of local actors which means that its application is time consuming and labour

**FIGURE 7** Overview of the application of the three methodologies to the case study in Sardinia. Notes: Colour shows details about scenarios. Shape shows details about configurations. Indirect Land Use Change (ILUC)-free feedstock is the share of the project biomass which is provided without causing ILUC. ILUC (ha) is the size of the area indirectly converted due to the biofuel project. No Irrigated scenario is provided for Low Indirect Impact Biofuel method since no areas can be irrigated. PAST, Project ASsessment Tool
intensive. This is true also for the time and labour-intensive application of ILUC PAST. However, LIIB applies restrictive definitions of eligible land use categories without the possibility to adapt them to context-specific elements that characterize each case. In the Sardinia case study, these features resulted in a large share of the Giant Reed feedstock to be considered of high ILUC risk. By employing land use categories in line with local conditions ILUC PAST provided a more accurate assessment. A more substantial limitation of the LIIB is the inability to provide quantitative estimates of ILUC making it impossible to compare options generating very different ILUC impacts but falling within the same category of (eligible or not eligible) land. Quantitative estimates of ILUC of individual projects are provided by both ILUC PAST and iLUC Club. However, iLUC Club relies on simplifications and assumptions, which allow for a desk-based, fast and easy application, but limit the ability to capture context-specific land use dynamics and, thus, potentially hinder the accuracy of results. However, this conclusion should be subject to further investigations on a variety of case studies. Moreover, the lack of engagement activities means that the quantitative estimates of iLUC Club may not be in line with local knowledge and conditions. However, the most important limitation of the method is the inability to support the development of measures to improve the performance of individual supply chains. This knowledge is provided by ILUC PAST at the condition that sufficient resources are available for the collection of area-specific data and the engagement of local actors.

Although ILUC PAST seems to offer advantages compared to existing methods for project level assessment, we should carefully consider whether the information it provides is useful to support effective decision-making by expanding alternatives, affecting choices and enabling decision makers to achieve desired outcomes (McNie, 2007). This is a critical issue in view of the large number of methodological approaches already developed to deal with the ILUC of biofuel. In this context, it is helpful to refer to three factors determining whether information is useful for decision-making—salience, legitimacy and credibility (Cash et al., 2002, 2003). Saliency—or the relevance of information for an actor’s decision choices, is considered an intrinsic feature of the knowledge produced by ILUC PAST. It provides knowledge of both quantitative impacts and qualitative causal chains to the private and public decision makers with agency on the LUC of individual projects. This feature represents a clear improvement compared to the saliency of LIIB and iLUC Club respectively. The legitimacy of this information—or whether actors perceive the process of knowledge development as unbiased and meeting standards of political and procedural fairness, is promoted in ILUC PAST by engaging in the assessment a broad sample of decision makers and those affected by the biofuel project, that is, stakeholders. In this way, it improves on the legitimacy of iLUC Club in which no social engagement is conducted. Finally, credibility—or whether the knowledge, along with the facts, theories and causal explanations invoked in the analysis, is considered trustworthy and plausible, is of critical importance, in particular, in controversial arenas where credibility is hard to establish due to considerable uncertainties and scientific disagreement (Clark, Ronald, David, & Frank, 2002). Existing ILUC models, either EEM or DM, are affected by large uncertainties about input data and/or causal relationships, which fuel scientific disagreement hindering effective decision-making. ILUC PAST does not ignore uncertainties, but seeks to make them more manageable applying a combination of approaches including scenario analysis, sensitivity analysis and stakeholder engagement. In the case study, two scenarios were developed based on alternative crop management practices, while sensitivity analysis was used to evaluate how uncertainties around key factors affect the final results. These analyses were framed and supported by the engagement of local stakeholders and experts in the (collaborative) building of the SD model and validation activities. The combined use of these techniques promoted agreement among representatives of local expert and stakeholder groups about facts, theories and causal explanations. This agreement was critical for the production of knowledge considered credible from multiple perspectives within the local context. In this way ILUC PAST improves on the level of credibility achievable by iLUC Club.

Over the past decade, concerns about the negative side effects of biofuel deployment have motivated the development of advanced technologies. Where biofuel technologies use local feedstocks or feedstocks traceable to a specific location, ILUC PAST can be applied to assess their (I)LUC effects. In spite of being labour intensive and time demanding, the approach can support local decision makers by providing knowledge of the ILUC of individual projects that is sufficiently credible, salient and legitimate.

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