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S.S.D: AGR/02

RISK ASSESSMENT AND ENVIRONMENTAL IMPACT ANALYSIS OF ELECTRICITY GENERATION FROM BIOMASS SORGHUM

Candidate: Paolo Serra
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Academic Year 2014/2015

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This PhD thesis explores the use of sorghum (*Sorghum bicolour* (L.) Moench) as a dedicated bioenergy crop (to generate electricity), and highlights the benefits and risks associated with the use of early, medium-late and late sorghum genotypes.

Overall, the results of this thesis improve the knowledge management of biomass sorghum from the field through to the end use, and can be used to help address the different productive, economical and environmental issues related to the use of sorghum biomass to produce electricity by direct combustion**.**

Abstract

This PhD thesis explores the use of sorghum (*Sorghum bicolour* (L.) Moench) as a dedicated bioenergy crop (to generate electricity), and highlights the benefits and risks associated with the use of early, medium-late and late sorghum genotypes.

This thesis is performed on a modelling approach based on experimental trials carried out in the Po Valley between 2006 - 2010 and 2012 with the aim of exploring the production performance (biomass production) of three sorghum genotypes characterized by different earliness.

The main problem associated with the use of sorghum to generate electricity is the biomass moisture content at the time of harvest (about 70%). To reach an optimal moisture content for storage it is essential to dry the biomass on the field to a moisture content of ≤ 30%.

In this thesis, a specific "sorghum haying model" was developed to simulate the dynamic and the duration of the field drying process of three sorghum genotypes characterized by contrasting earliness (early, medium-late and late). In conjunction with the biomass yield data obtained from the CropSyst model, the three genotypes were then evaluated in terms of their production, and the probability of being dried to a suitable moisture content for bailing.

Further to this a risk assessment was performed to determine the number of hectares needed (for each genotype) to guarantee a biomass production of 64000 Mg DM y^{-1}. In addition a specific study was performed to simulate the probability to exceed (P_e, %) this production. The "sorghum haying model" was coupled to the CropSyst model and run on a mosaic of virtual farms located in the target supply are, to simulate the biomass losses (respiration and mechanical losses) and haymaking failures (total and partial) and consequently to quantify the amount of dry baled biomass available for the power plant.

Having a large quantity of baled biomass available for combustion at the power plant is essential also to obtain a positive energy balance and an economically profitable production.

Identification of the energy input and output involved in a bioenergy system is fundamental to quantify the sustainability of the entire biomass supply chain. In this thesis a simplified cradle to farm gate energy balance was performed to quantify the total energy input and output with the aim of estimating, for all three sorghum genotypes, three energy based indices; Energy Return on Investment (EROI), Net Energy Gain (NEG) and Energy Use Efficiency (EUE).

To increase the readability of the study, a complete cradle to grave Life Cycle Assessment (LCA) was performed to evaluate the environmental impact of the three sorghum genotypes involved in this study. In addition, the LCA takes into consideration the use of winter wheat straw as an additional biomass source to satisfy the total biomass power plant needs (94000 Mg DM y^{-1}) in particular, soil organic carbon change (ΔSOC) due to removal of the straw from the field. ΔSOC was also calculated for the incorporation (into the soil) of the sorghum biomass that was not baled (haymaking failure). To test the effect of the many assumptions defined in the LCA model, a sensitivity analysis was performed on several parameters to explore their individual impact on the environment.

Early genotypes had the highest probability (P_e= 0.66) of being baled at a moisture content ≤ 18% followed by medium-late and late genotypes. Early genotypes also had the highest energy performance (EROEI: 14.38; NEG: 205.6 MJ $ha^{-1}y^{-1}$; EUE: 1.06 GJ Mg^{-1}DM y^{-1}) and the highest probability to exceed (P_e= 0.38) the threshold of 64000 Mg DM y^{-1}. The highest energetic and probability results were reached by the early genotype because it was with this genotype that the highest baled biomass (14.04 Mg DM ha^{-1}) was achieved due to the low incidence of haymaking failures. LCA results did not show significant differences between sorghum genotypes in terms of GHG emissions, though the lowest GHG emissions were calculated for the late genotype as a consequence of its high incidence of haymaking failures. Biomass left on the field due to haymaking failures is later incorporated into the soil, increasing SOC, and mitigating the SOC decrease due to straw removal.

Overall, the results of this thesis improve the knowledge management of biomass sorghum from the field through to the end use, and can be used to help address the different productive, economical and environmental issues related to the use of sorghum biomass to produce electricity by direct combustion**.**

Glossary

AP	Acidification Potential
BBCH	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie
CGMS	Crop Growth Monitoring System
d	Index of Agreement
DeNO$_x$ SNCR	Selective No Catalytic Reaction
DM	Dry Matter
DOY	Day of Year
E	Mean Error
EC	European Commission
EF	Modelling Efficiency
EROEI	Energy Return on Energy Investment
EROI	Energy Return on Investment
ERSAF	Regional Agency for Agriculture and Forest
EU	European Union
EUE	Energy Use Efficiency
FWE	Freshwater Eutrophication
GDD	Growing Degree Days
GHG	GreenHouse Gases
GWP	Global Warming Potential
ILUC	indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISTAT	Italian Institute for Statistics
JRC	European Commission, Joint Research Centre
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MAE	Mean Absolute Error
ME	Marine Eutrophication
NEG	Net Energy Gain
NPE	Net Primary Energy
nRMSE	Normalize Root Mean Square Error
PE	Probability of exceedance
PER	Primary Energy Requirement
PM/RI	Particular Matter/Respiratory Inorganic
POFP	Photochemical Ozone Formation Potential
RED	Renewable Energy Directive (2009/28/EC)
RES	Renewable Energy Souces
RMSE	Root Mean Square Error
SOC	Soil Organic Carbon
SSF	Storage Satellite Facility
ΔSOC	Soil Organic Carbon change

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CHAPTER 1

General Introduction

1.1 General introduction

Since the pre-industrial era Anthropogenic greenhouse gas (GHG) emissions have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2014). The continuous use of fossil fuels, for energy purposes and services supply, increases the CO_2 concentration in atmosphere (Fargione *et al*., 2008).

In a context characterized by a strong dependency on the use of fossil fuels, climate change, food security and energy provision are driving forces to be addressed in order to find and/or implement a sustainable way to produce energy.

The reduction of carbon emissions (Schiermeier *et al*., 2008), an increase in energy security and provision (Eaves and Eaves, 2007) and minimization of the dependence on finite fossil fuel reserves (Mackay, 2008), are the three driving forces to address the interest on renewable energy sources (Pogson *et al*., 2013). As indicated in the Renewable Energy Directive (EU-RED, 2009), Europe considers Renewable Energy Sources (RES) able to reduce fossil energy consumptions and greenhouse gas (GHG) emissions (Harmsen *et al*., 2011). In this frame, biomass is considered an important source of energy (Sims *et al*., 2006), materials and chemicals production (Cherubini, 2010a) and today biomass is taken into account as a promising and interesting energy source to mitigate greenhouse gas emissions (Cherubini *et al*., 2009, Creutzig *et al*., 2014).

Dedicated bioenergy crops have the largest technical potential to produce bioenergy and a wide range of bioenergy crops are regarded as suitable to produce bioenergy: perennial C4 crops, short rotation coppices (SRCs), semi-perennial forage crops and annual C4 or C3 crops (Karp and Shield, 2008; Sanderson and Adler, 2008; Zegada-Lizarazu *et al*., 2010a). The choice of more adequate biomass crops depends on the end-use and bio-conversion option of interest (McKendry, 2002) and from some pre-requisites listed by Venturi and Venturi (2003) and Cherubini *et al*., (2009).

According to Karp and Shield, (2008) bioenergy crops can be grown for two contrasting markets: power generation (electricity, heat, and combined heat and power) and liquid transport fuels. The three main conversion processes to produce energy from bioenergy crops are: 1) thermochemical (direct combustion, gasification and pyrolysis), 2) biochemical (anaerobic digestion and fermentation), and 3) physicochemical (mechanical and chemical extractions) (Nguyen *et al*., 2010).

The factors that influence the choice of the conversion process are: the type and quantity of biomass feedstock; the desired form of the energy, i.e. end-use requirements; environmental standards; economic conditions; and project specific factors (McKendry, 2002).

From an environmental point of view, the use of biomass for energy generation is often defined as “carbon neutral” (Nguyen *et al*., 2010). However, this assumption has been proven wrong in many cases. Concerning forest biomass, for instance, the assumption of instantaneous carbon neutrality does not apply due to the time delay between emission and re-absorption of biogenic carbon (see for example Agostini *et al.*, 2014). Concerning biomass cultivated on existing cropland, the main issue is related to market-mediated effects linked to the displacement of such biomass (or land) from the existing use. In many cases this has been associated to additional emissions from the so-called indirect Land Use Change (iLUC) impact.

Furthermore, current biomass production still depends on input resources (e.g. fossil fuels) that are associated with environmental emissions (Cherubini *et al.*, 2009). The GHG emissions generated during the production of dedicated bioenergy crops are - soil nitrous oxide (N_2O) emissions, soil CO_2 and methane (CH_4) fluxes, and CO_2 emissions derived from agricultural inputs and agricultural machinery operations (Robertson *et al.* 2000, Del Grosso *et al.* 2001, West and Marland 2002, Stehfest and Bouwman, 2006).

Alternative energies (e.g. biofuels) are generally proposed as an option to replace fossil fuels, but little attention is given to their low net energy potentials (Zagada-Lizarazu *et al.*, 2010b).

Crop management and production is characterized by the high input of fossil energy, which is consumed as “direct energy” (fuel and electricity used on the farm) and as “indirect energy” (energy expended beyond the farm for the manufacture of fertilizers, plant protection agents, machines, etc.) (Hülsbergen *et al.*, 2001).

A budge analysis that accounts for energy input and output is fundamental to quantify the sustainability of the entire biomass supply chain, as reported by Arodudu *et al.* (2013), who suggested using energy-based indices as measures of bioenergy potential. The estimation of energy indices such as Energy Return on Invested (EROI) (Hall *et al.*, 2009), Net Energy Gain (NEG) (Scholz and Ellerbrock, 2002) and Energy Use Efficiency (EUE) (Monti and Venturi, 2003) became fundamental to evaluate the efficiency of the bioenergy systems.

In the scientific community, Life Cycle Assessment (LCA) is recognized as the most appropriate analytical tool for determining the direct and indirect GHG emissions to quantify the environmental impacts of biomass crops production (Cherubini *et al.*, 2009, Cherubini, 2010b, Rettenmaier *et al.*, 2010).

The LCA methodology is standardized and described under the standards of the International Standard Organization, ISO 14040/44 (ISO 2006a; 2006b). LCA is used to evaluate the environmental impacts and other potential factors related to the product’s life cycle energy balance, including raw materials, production, consumption, and waste utilization.

The International Reference Life Cycle Data System (ILCD) has therefore been developed to provide guidance for consistent and quality assured Life Cycle Assessment data and studies (ILCD, 2010).

However, LCA has some inherent sources of uncertainty linked to: the exogenous data used to model the background system (normally from commercial databases), the unavoidable assumptions and the approach used to model the system under analysis (Basset-Mens *et al.*, 2009).

Uncertainty is particularly relevant in the case of agricultural systems because of the great variability in the farming practices and the local soil and climate conditions (Flysjö *et al.*, 2011). Comparing results of different LCA studies may be misleading as estimates may vary significantly depending on the assumptions, models and data used (Flysjö *et al.*, 2012). However, comparing systems within the same study (with the same assumptions, input data and models), may lead to reliable conclusions that can be used to provide scientifically sound support to policy makers.

1.2 Context and description of the thesis

In Italy the interest to use biomass to produce bioenergy increased following the 2006 European Reform of sugar Common Market Organisation (320/2006/EC) when a large area of agricultural land previously cultivated with sugar beet (*Beta vulgaris* L.) became available for other purposes. In particular the Regulation 318/2006/EC made Italian sugar production uncompetitive and authorized a drastic reduction of the production, thanks to specific EU funds for divesting the establishments, decommissioning and cleaning of the industrial areas. Other EU funds were provided to reactivate the agro-industrial sector affected. In response to this in March 2006 the Italian government issued the Law 81/2006, aimed at promoting the conversion of disused sugar factories in to other agro-industrial activities.

The work presented in this thesis was commissioned by the Lombardy Region as part of a feasibility study to convert one of the sugar factories to a biomass power plant. Farmers' Associations and the Lombardy Region imposed the constraint that the power plant should operate on feedstock produced or recovered on farm, within the ex-sugar factory supply area.

It was calculated that to satisfy 70% of the needs of the biomass power plant, characterized by a thermal capacity of 15 MW_{el} (50 MW_{th}), 64000 Mg DM y^{-1} of sorghum (*Sorghum bicolour* (L.) Moench) (LHV_{dry} 15.7 MJ kg^{-1}) would be needed (Original approved technical details of sorghum power plant, 2012). In this study it was assumed that the residual 30% of biomass would be covered by winter wheat (*Triticum aestivum* L.) straw that can also be supplied in the region.

The biomass power plant in question was projected to have a thermal capacity of 15 MW_{el} (50 MW_{th}) and be equipped with a $DeNO_x$ Selective No Catalytic Reaction (SNCR) system to abate NO_x emissions. This is required by the special conditions in the Po Valley where particulate matter emissions and ozone formation are serious concerns (Mircea *et al.*, 2014). The SNCR process, for NO_x removal, uses an aqueous solution of urea and has been extensively applied in a range of industrial applications (Mendoza-Covarrubias *et al.*, 2011). While high NO_x abatement can be obtained by SNCR, potential by products of the $DeNO_x$ reactions include ammonia and N_2O which could offset some of the environmental benefits of the technology.

Sorghum is the fifth most widely cultivated cereal in the world with a production in 2013 of 62.3 million MT on 42.2 million hectares, with an average yield of 1.48 MT ha^{-1} (FAOSTAT, 2013).

Sorghum is an annual multipurpose herbaceous crop used for food, fodder and as a bioenergy crop. Based on utility patterns, sorghum can be broadly classified as grain sorghum, sweet sorghum, forage sorghum, brown midrib sorghum and energy sorghum (Rao *et al.*, 2015).

In this thesis the interest was focused on the bioenergy potential of energy sorghum as a dedicated biomass crop to generate electricity via direct combustion in a biomass power plant.

Among C4 annual bioenergy crops, sorghum has been receiving increasing attention as dedicated ligno-cellulosic bioenergy crop (Rooney *et al.*, 2007). Sorghum which has a growing cycle similar to that of traditional food crops, demonstrates a high potential energy related both for anaerobic digestion, second generation bioethanol production (Amaducci *et al.*, 2000, Davila-Gomez *et al.*, 2011, Agostini *et al.*, 2015), and electricity generation by combustion (Venturi and Venturi, 2003, Bennett and Anex, 2009, Zagada-Lizarazu and Monti, 2012), given its high potential for dry matter production (Gill *et al.*, 2014).

The interest of biomass sorghum as dedicated bioenergy crop is due to its low input requirement, drought tolerance, high water use efficiency, the ability to maintain high yields under a wide range of environmental conditions (Habyaimana *et al.*, 2004, Rooney *et al.*, 2007, Quaranta *et al.*, 2009, Zagada-Lizarazu and Monti, 2012, Rocateli *et al.*, 2013), ordinary introduction in the common crop rotation (Zagada-Lizarazu and Monti, 2011, Gill *et al.*, 2014) and its capacity to produce high yield of biomass in as few as 90 to 100 days (Wight *et al.*, 2012).

In Italy, Habyarimana *et al.*, (2004) showed the production of nine biomass sorghum genotypes to range from 18.6 to 28.2 Mg DM $ha^{-1}y^{-1}$ under well-watered conditions in four locations in Italy in 2001. Bentini and Martelli, (2013) showed a biomass production of 24.8 Mg DM ha^{-1} under rain-fed conditions in the Po Valley in 2013. In a recent study, Amaducci *et al.*, (2016) showed an average biomass sorghum production of 21.6 Mg DM ha^{-1} under different nitrogen and irrigation levels in Po Valley between 2006 and 2010.

One of the main constraints hindering the use of biomass sorghum for electricity generation by combustion is the high moisture content at harvest time approximately 70%, wet basis (with slight variations among genotypes and harvest dates) (Quaranta *et al*., 2009, Pari *et al*., 2011, Zagada-Lizarazu and Monti, 2012). Cut sorghum has to be dried in field until it reaches a suitable moisture content for long-term storage (Bonner and Kenney, 2012). The field drying process is part of the work chain that includes conditioning, tedding, windrowing, and collecting (Assirelli *et al*., 2013). The dynamics and consequently the duration of the field drying process depends on the weather conditions – the risk of rain during the drying period gradually increases with harvest time (Pari *et al*., 2010).

To guarantee that a suitable moisture content is reached it is essential to exploit all the factors that are known to affect the drying process, including harvest mechanization technology and biomass sorghum genotype choice.

In Italy, biomass sorghum harvest mechanization technology was improved with the realization of an innovative mower conditioner (Pari *et al*.,2010, Assirelli *et al*., 2013). This machinery has intensive mechanical rollers that perform a conditioning treatment, creating cracks along the stems and leaves increasing the surface area for evapotraspiration, and speeding up the field drying process (Mercel *et al*., 2011, Pari *et al*., 2011, Bonner and Kenney, 2012, Assirelli *et al*., 2013).

Regarding sorghum genotype earliness, an early genotype, being harvested commonly in a time window when the weather conditions are favourable for on-field drying minimizes the risk of exposing the harvested biomass to adverse weather conditions. It should be noted however that the biomass production of early genotypes can be lower than that produced by late sorghum genotypes (Quaranta *et al*., 2009).

The risk of not reaching a suitable biomass moisture content during the field drying process is coupled to the risk of not achieving a determinate target biomass production, which in this work was 64000 Mg DM y^{-1}. Risk assessment analysis is the process of assessing such factors, whereby risk management is applied to reduce the consequences of adverse events identified by the risk analysis (Jones, 2001). Within the agroecosystem related studies, the risk assessment analysis may concern the climate change impact on crops yield (Jones, 2001, Li *et al*., 2009, Langholz *et al*., 2014), the pesticide seeping into surface water (Solomon *et al*., 1996), the use of genetically modified organisms (GMO) into the environment (Wolt *et al*., 2010), and the evaluation of bioenergy systems sustainability (Elghali *et al*., 2007). In this study the risk assessment evaluated the level of risk related to different sorghum genotypes in relation to the possibility of annually producing enough biomass to satisfy or exceed the needs of the power plant. The development of a risk assessment framework can provide practical advice for policy makers, planners and the bioenergy industry, and thus support policy development and bioenergy deployment at different scales (Elghali *et al*., 2007, Langholz *et al*., 2014).

The next step of PhD thesis was to carry out an analysis of environmental impact (EI) and energy performance (EP) of the entire bioenergy supply chain (sorghum complemented by straw) through a complete Cradle to Grave Life Cycle Assessments (LCA).

The LCA study was performed using GaBi 6 software (Thinkstep, 2015) and the following impact categories have been assessed: global warming potential (GWP), acidification potential (AP), freshwater eutrophication (FE), marine eutrophication (ME), particulate matter (PM) and photochemical ozone formation potential (POFP). Regarding EP, Energy Return on Energy Investment (EROEI) was calculated.

1.3 Objectives and framework of the thesis

The thesis has a single logical thread focused on the use of biomass sorghum to generate electricity by direct combustion in a biomass power plant. The thesis starts with the determination of the dynamics of the field drying process of three biomass sorghum genotypes characterized by different earliness (early, medium-late and late) and continues with the exploration of the production risk and the energy performance of biomass sorghum cultivated to satisfy the power plant feedstock needs. The next step is the determination of the environmental impact and energy performance of the entire sorghum biomass supply chain trough the Life Cycle Assessment (LCA) approach.

This work has been developed in the Po Valley (Lombardy Region, Italy), the area in which biomass sorghum was projected to be cultivated to provide new opportunities for the areas previously cultivated with sugar beet.

The thesis is presented in 3 Chapters; the specific objectives of each chapter are presented here below:

- Chapter 2 explores the dynamics of the field drying process of three biomass sorghum genotypes characterized by different earliness (early, medium-late and late). A specific model, “sorghum haying model”, was developed to determine which sorghum genotype provides the best trade-off between biomass production and moisture content at baling time.

- Chapter 3 presents a risk assessment analysis to explore the production risk and the energy performance of sorghum cultivated to supply the power plant. The risk assessment analysis was carried out in order to estimate the cropping surface needing to be planted annually with sorghum and the probability that the sorghum harvested on this target cropping surface can provide more than 70% of the power plant needs. The energy performance of the baled biomass was evaluated by calculating Energy Return on Investment (EROI), Net Energy Gain (NEG) and Energy Use Efficiency (EUE) along the whole production system with an approach from cradle to farm gate.

- Chapter 4 describes the environmental impacts and energy performance obtained from a Life Cycle Assessment of different bioenergy supply chains fed by the three sorghum genotypes in question (early, medium-late, late). The sorghum supply chains are complemented by cereal straw to cover the needs of the power plant.

Finally Chapter 5 concludes this thesis.

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CHAPTER 2

Genotype earliness effect on field drying of biomass sorghum

The chapter is submitted as:
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Genotype earliness effect on field drying of biomass sorghum

Abstract

A major constraint to the use of biomass sorghum genotypes (*Sorghum bicolor* (L.) Moench) to generate electricity by direct combustion is the high biomass moisture content at harvest that, under unfavourable weather conditions during field drying, limits the possibility to achieve a suitable moisture content for bailing.

In this work the CropSyst model, calibrated and validated with data collected in experimental trials conducted in the Po Valley (northern Italy), was used to simulate biomass production of three sorghum genotypes of contrasting earliness (early, medium-late and late). In order to simulate the dynamics of biomass moisture content during field drying, a specific model, "sorghum haying model", was developed, validated and calibrated.

The two models combined were used to simulate, for three sorghum genotypes of contrasting earliness (early, medium-late and late), biomass production and the probability to achieve during field drying a biomass moisture content suitable for bailing.

In a long term simulation (140 years), the late sorghum genotype achieved the highest biomass production (16.5 Mg DM ha^{-1}) followed by the medium-late (15.4 Mg DM ha^{-1}) and early (15.1 DM Mg ha^{-1}) genotype. The early genotype had the highest probability (0.66) of being baled at a moisture content ≤ 18%, followed by the medium-late (0.53) and late (0.37) genotypes. The early genotype, also having the shortest average field drying (9.2 days), was considered the most suitable for the selected environmental conditions.

Keywords: *Sorghum bicolour*, genotype earliness, model simulation, biomass moisture content, field drying, combustion

2.1 Introduction

Among annual biomass species, sorghum (*Sorghum bicolor* (L.) Moench) could have an important role in energy production as a dedicated lignocellulosic energy crop in anaerobic digestion, second generation bioethanol production (Amaducci *et al.*, 2000, Davila-Gomez *et al.*, 2011, Zagada-Lizarazu and Monti, 2012, Agostini *et al.*, 2015) and in heat and power generation by direct combustion (Zagada-Lizarazu and Monti, 2012).

Sorghum is a C4 herbaceous plant of tropical origins, yet it readily adapts to different growing conditions (Habyaimana *et al.*, 2004a,b, Rooney *et al.*, 2007, Rocateli *et al.*, 2013). This large adaptability is due to its relatively low agronomic requirements and inputs compared to other crops (Quaranta *et al.*, 2009, Zagada-Lizarazu and Monti, 2012).

However, one of the main constraints hindering the use of biomass sorghum to generate heat and power via direct combustion is the high moisture content at harvest time (around 70%, wet basis) with slight variation among genotypes and harvest dates (Quaranta *et al.*, 2009, Zagada-Lizarazu and Monti, 2012). Field drying is therefore essential to reach the necessary optimal moisture content at baling time (Inman *et al.*, 2010) and consequently to guarantee long-term storage of sorghum (Bonner and Kenney, 2013). The high moisture content during storage stage determines biomass damages such as spores and fungus formation and dry matter losses that leading to potential problems in the power plant technological devices (Hess *et al*., 2007, Rentizelas *et al*., 2009).

To minimize quantitative and qualitative damage and losses (Lemus, 2009) during storage stage, the moisture content of biomass at time of baling has to be between 15-20%$_{wb}$ (Rocateli *et al*., 2013) as a lower limit and 30%$_{wb}$ as an upper limit (Assirelli *et al*., 2013).

To reach this moisture content a correct harvest mechanization technology is fundamental (Assirelli *et al.,* 2013). Like other herbaceous crops (i.e. fodder crops) also biomass sorghum mechanization uses a common work chain that includes conditioning, tedding, windrowing, and harvesting (Assirelli *et al*., 2013). Due to the considerable thickness of sorghum stalks (Lardy and Anderson, 2003) an intensive conditioning treatment at harvest is needed (Pari *et al*., 2011, Assirelli *et al.,* 2013) to reduce the field drying time.

Field drying duration is also affected by climatic conditions at harvesting; if using an early sorghum genotype the harvest tends to be in a time window when the risk of exposing the cut biomass to adverse weather conditions is minimal (Pari *et al*. 2010), though the biomass production can be lower than that produced by late genotypes (Quaranta *et al*., 2009). There must therefore be a trade-off between biomass production and the risks associated with field drying process.

A number of studies have dealt with the dynamics and mechanization of field drying sorghum biomass (Mercer *et al.,* 2011, Bonner and Kenney, 2012, Rocateli *et al*., 2013, Assirelli *et al*., 2013, Pari *et al*., 2010, Pari *et al*., 2011), but a study to model field drying in relation to sorghum genotype earliness has not yet been carried out.

The objective of this study was to simulate the biomass production and the field drying dynamics in relation to the earliness of three biomass sorghum genotypes. The CropSyst model was used to simulate biomass sorghum production while a new model, “sorghum haying model”, was developed to simulate the duration and the dynamics of field drying the sorghum biomass. The sorghum haying model was then used, in combination with CropSyst, to identify the optimal sorghum genotype to reach the best trade-off between biomass production and moisture content at baling time.

2.2 Materials and Methods

The work presented in this article is based on the use of two simulation models; CropSyst (Stockle *et al*. 2003) and “sorghum haying model”. The first was used to simulate the biomass production of three sorghum genotypes characterized by different earliness (early, medium-late and late), while the second was developed to simulate field drying and net harvestable biomass (baled) of biomass sorghum.

2.2.1 CropSyst model

CropSyst is a process-based, multi-year, multi-crop, daily time step cropping system simulation model developed to evaluate the effects of different pedoclimatic and management conditions on crop growth and on environmental impact (Stockle *et al.* 2003).

In this work the calibration of CropSyst was carried out on a medium-late sorghum genotype (Biomass 133, commercialized in Italy by Syngenta) using the measured crop growth stages and total biomass production (see below) and CropSyst default parameters.

Crop growth was modelled through thermal time accumulation by counting the growing degree days-GDD (thermal units) for different phenological stages that were estimated from the base temperature (°C) as a lower limit and cut off temperature (°C; optimum temperature for thermal time accumulation) as an upper limit and daily mean temperature. Other crop parameters were estimated using the Scilab (Scilab Enterprises, 2012) function *fminsearch* with the classical approach to minimize the target function *f*:

$$f = \sum_{i}^{n} (Yobs_i - Ysim_i)^2 \tag{2.1}$$

where $Yobs_i$ and $Ysim_i$ are respectively the observed and simulated values of total biomass at crop maturity and n is the number of observations. Parameters were changed in the optimisation process starting from the default parameter values and within a biologically logical range. Table 2.1 lists the values of all the parameters applied in the CropSyst model, indicating them as default values (D), calibrated values (C) and "local experience" values (L).

2.2.1.1 CropSyst calibration

To calibrate CropSyst, biomass production data of a medium-late sorghum genotype (Biomass 133) was collected in a mid-term experimental trial conducted in Gariga di Podenzano (PC), in the Po Valley Italy (44°58'59"N, 9°40'48''E, altitude 84 m a.s.l.) between 2006 and 2010 (Amaducci *et al.*, 2016). Biomass 133 was compared to an hybrid maize (Arma – Syngenta FAO class 700) in a split-split-plot design with four replicates (only three in 2009) to evaluate the effect of irrigation and nitrogen fertilization on biogas production. Different nitrogen and irrigation levels in factorial combinations were applied. The biomass dry matter production (Mg DM ha^{-1}) was estimated by harvesting three rows per sub-subplot (8 m^2 in total per sub-subplot) at hard dough stage (BBCH87).

Table 2.1 - CropSyst model parameters for three sorghum genotypes and source of information (C: calibrated parameters; D: CropSyst default values; L: "local experience").

Parameter	Determination	Genotype			Unit
		Early	Medium-late	Late	
Aboveground biomass-transpiration coefficient (BTR)	C	10.768	10.768	10.768	kPa kgm^{-3}
Light to aboveground biomass conversion (LtBC)	C	3.811	3.811	3.811	gMJ^{-1}
Actual to potential transpiration ratio that limits leaf area growth	D	0.95	0.95	0.95	–
Actual to potential transpiration ratio that limits root growth	D	0.5	0.5	0.5	–
Optimum mean daily temperature for growth (Topt)	C	22	22	22	°C
Maximum water uptake	D	12	12	12	mm per day
Leaf water potential at the onset of stomatal closure	D	1900	1900	1900	J kg^{-1}
Leaf duration	D	1400	1400	1400	°C-days
Wilting leaf water potential	D	2700	2700	2700	J kg^{-1}
Maximum rooting depth	L	2	2	2	m
Maximum expected leaf area index (LAI)	L	7	7	7	m^2 m^{-2}
Fraction of maximum LAI at physiological maturity	L	0.9	0.9	0.9	–
Specific leaf area (SLA)	L	22	22	22	m^2 kg^{-1}
Stem/leaf partition coefficient (SLP)	D	2	2	2	–
Extinction coefficient for solar radiation (k)	D	0.5	0.5	0.5	–
ET crop coefficient at full canopy	D	1	1	1	–
Degree days emergence	L	79	79	79	°C-days
Degree days begin flowering	L	910	1012	1400	°C-days
Degree days begin filling	L	1187	1345	1500	°C-days
Degree days begin senescence	L	1134	1285	1550	°C-days
Maturity	L	1600	1725	1950	°C-days
Base temperature (Tbase)	D	5.76	5.76	5.76	°C
Optimal temperature	C	26.3	26.3	26.3	°C
Cutoff temperature (Tcutoff)	D	32	32	32	°C
Maximum uptake during rapid linear growth	C	8.182	8.182	8.182	g m^{-2} day^{-1}
Nitrogen demand adjustment	C	0.4943	0.4943	0.4943	–
Phenologic sensitivity to water stress	D	0	0	0	–

2.2.1.2 CropSyst validation

To validate CropSyst, Biomass 133, a medium-late genotype, was grown in twenty experimental fields (on a total of 39 ha) located in the Po Valley (Lombardy Region, Italy) in 2010. Experimental fields were prepared by conventional tillage (30 cm deep ploughing followed by 1 passage of a tandem disk harrow and 1 passage of a power harrow) and sowing was performed with a pneumatic drill (Maschio Gaspardo SP Dorata 6 rows) using 10 kg ha^{-1} (20 seeds m^{2}) with an inter-row distance of 0.7 m and inter-plant distance of 0.1 m. Tables 2.2a and 2.2b provide details of the soil types of the 20 experimental fields; in addition Table 2.2b lists the preceding crop, the sowing date, the total amount of nitrogen applied during the experiment, and the irrigation source.

Above-ground biomass production was estimated by manual cutting and sampling of four representative areas of 10 m^{2} randomly taken from each experimental field. Approximately 600 g from each biomass sample was weighed, dried at 105°C until reaching a constant weight, and re-weighed to calculate dry matter content (%) and subsequently (Mg DM ha^{-1}).

2.2.1.3 Simulation of two additional sorghum genotypes

In order to simulate two additional sorghum genotypes (early and late) using the same parameterization obtained from the calibration of the medium-late genotype, Biomass 133, some phenological characteristics were changed, as reported in Table 2.1. The “early” genotype was characterized by a growth cycle of 125 GDD less than Biomass 133; the “late” genotype was characterized by a growth cycle of 225 GDD more than Biomass 133. Harvesting of all three genotypes (early, medium-late and late) was carried out at hard dough stage (BBCH87).

The model performance during both calibration and validation was successively evaluated according to the statistical indexes proposed by Yang *et al.*, (2014).

2.2.2 Sorghum haying model description

The sorghum haying model simulates the processes of drying and re-wetting of sorghum on the basis of weather (temperature, solar radiation, rain, wind speed and relative air moisture) and management variables (i.e. cutting and baling time, biomass moisture content).

Sorghum haying model was developed in Scilab programming language (Scilab Enterprises, 2012) and integrated with dynamic equations performed with the Scilab *ode* function (ordinary differential equation solver).

To simulate drying of sorghum in swaths we followed the simplified approach of the single layer, as described by Barr and Brown (1995). Thompson (1981) reported that the single-layer model performs as well as a multi-layer model under most conditions.

The biomass to be dried is represented with only two state variables - total dry matter, W_b (kg m^{-2}) and the water mass contained in the biomass, W_{H2O} (kg m^{-2}).

The biomass moisture, M_w (kg H_2O (kg DM)$^{-1}$) during haying process was calculated on a dry matter basis, with the ratio:

Table 2.2a - Description of soils involved in this work. In this table are showed texture composition (sand, silt and clay) per each soils and considering the first soil horizon Ap. In addition is indicate organic matter, carbon content expressed in % and USDA soil classification.

n°	Soil acronym	Soil horizon	Depth (cm)	Texture (%)			Organic Matter (%)		Bulk density (g cm^3)	Field capacity (m^3 m^{-3})	Wilting point (m^3 m^{-3})	USDA Classification
				Sand	Silt	Clay	SOC	SOM				
1	GOD1	Ap	55	27.2	40.9	31.9	0.90	1.55	1.31	0.33	0.18	Fluventic Haplustepts
2	NOA1	Ap	50	19.8	36.8	43.4	1.23	2.11	1.24	0.41	0.26	Udic Calciusterts
3	RGI1	Ap	40	10.3	61.5	28.2	0.69	1.18	1.30	0.33	0.16	Udic Paleustalfs
4	SGD1	Ap	45	12.8	49.8	37.4	1.42	2.44	1.27	0.37	0.21	Fluvaquentic Endoaquepts
5	VIC1	Ap	55	2.2	64.4	33.4	2.80	4.81	1.26	0.36	0.18	Typic Endoaquepts
6	VRR1	Ap	15	28.1	56.7	15.2	1.20	2.06	1.31	0.33	0.16	Fluvaquentic Haplustepts

Table 2.2b - Description of farms involved in the experimental trials in 2010 in the Po Valley (Lombardy Region, Italy). In the table were reported the geographical position, kind of soil, weather station, biomass sorghum preceding crop and total biomass observed and simulated of the genotype Biomass 133.

Field n°	Latitude (°)	Longitude (°)	Soil acronym	Weather station	Previous crop	Sowing date	Total applied nitrogen (Kg ha^{-1})	Irrigation regime	Dry matter production (Mg ha^{-1})	
									Observed	Simulated
1	45°05'58"	9°08'26"	GOD1	jrc75106	Wheat	19-May	80	rainfed	20.2	20.5
2	45°01'49"	8°93'31"	RGI1	jrc75107	Wheat	26-May	81	rainfed	21.8	21.1
3	45°05'36"	9°36'95"	NOA1	jrc75106	Maize	12-May	117	rainfed	21.8	21.2
4	44°99'77"	8°98'11"	GOD1	jrc75106	Wheat	04-Jul	70	1 irrigation (*)	11.1	15.4
5	45°00'60"	8°92'74"	SGD1	jrc75106	Soybean	21-May	90	rainfed	21.5	24.8
6	45°03'95"	8°94'76"	VRR1	jrc76107	Tomato	14-May	120	rainfed	20.1	21.6
7	45°10'79"	9°18'51"	SGD1	jrc75107	Wheat	30-May	0	rainfed	20.0	19.4
8	45°07'61"	9°17'14"	SGD1	jrc75107	Barley	14-May	165	rainfed	22.3	20.4
9	45°07'70"	9°20'84"	GOD1	jrc76106	Soybean	23-May	170	rainfed	18.8	19.7
10	45°04'42"	8°94'71"	NOA1	jrc75106	Tomato	21-May	100	rainfed	22.4	21.7
11	44°99'83"	8°98'35"	VRR1	jrc75106	Wheat	15-Jun	170	1 irrigation (*)	11.8	13.8
12	45°07'19"	9°03'89"	VIC1	jrc75106	Rice	24-May	36	rainfed	20.6	22.4
13	45°09'37"	9°02'57"	VRR1	jrc75106	Soybean	11-May	60	rainfed	22.5	21.4
14	45°06'24"	8°97'33"	GOD1	jrc75107	Wheat	17-May	105	rainfed	26.9	22.6
15	45°05'03"	9°15'13"	GOD1	jrc75107	Maize	14-May	54	rainfed	17.6	21.3
16	45°05'83"	9°23'74"	VRR1	jrc76107	Wheat	23-May	110	rainfed	20.8	19.9
17	45°14'74"	9°16'08"	GOD1	jrc75106	Wheat	16-May	0	rainfed	21.8	21.2
18	45°03'12"	9°02'37"	SGD1	jrc75107	Onion	13-May	60	rainfed	12.7	14.0
19	45°07'07"	9°21'81"	SGD1	jrc75107	Wheat	17-May	150	rainfed	21.9	21.3
20	45°07'55"	9°14'17"	NOA1	jrc75106	Tomato	16-May	98	rainfed	21.9	21.2
								mean	19.9	20.2

(*) Performed to facilitate emergence ~ 20 mm.

$$M_W = \frac{W_{H2O}}{W_b} \tag{2.2}$$

The drying process was simulated by incorporating reference evapotranspiration (ET_h) in the computation, as featured in the pioneering work of Dyer and Brown (1977). In our model ET_h was used to estimate the evaporating power of the atmosphere. The driving force for the drying process is the difference in partial vapour pressure between the biomass and the surrounding air. When the internal vapour pressure is in equilibrium with the vapour pressure of the environment, the material has reached its equilibrium moisture content, M_{w0}, (Brooker, 1992).

We assumed that the evaporation rate, H_r (mm h^{-1}) is proportional to the difference between biomass moisture M_w and moisture at equilibrium, M_{w0}:

$$H_r = w \cdot ET_h \cdot (M_w - M_{w0}) \tag{2.3}$$

where ET_h (mm h^{-1}) is the hourly reference evapotranspiration, modelled using the standard procedure of Allen *et al.*, (1998) and w (mm $H_2O)^{-1}$ is an empirical parameter that could be used to incorporate different conditioning efficiencies (in our simulations w was a fixed value; see Table 2.3).

Values of M_{w0} were computed dynamically using the Equation (2.3) proposed by Bonner and Kenney (2013) in a study of moisture sorption by sorghum. They showed a relationship between equilibrium moisture content and water activity that was found to decrease with increasing temperatures, this was modeled with the Modified-Oswin formula (Oswin, 1946):

$$M_{w0} = (A + B \cdot T_a) \cdot \left(\frac{a_w}{1 - a_w}\right)^C \tag{2.4}$$

$$a_w = RH_h/100 \tag{2.5}$$

where a_w is the available water, T_a is the hourly air temperature, RH_h is the hourly relative humidity and A, B, C (see Table 2.3) are the parameters of the Modified-Oswin formula.

In the event of rainfall, on-field biomass is subjected to re-hydration. It is assumed that re-wetting occurs at a rate proportional to the depression of the forage moisture content M_w below the value of the maximum moisture (M_{w_max}) for sorghum biomass after a conditioning process (Barr *et al.*, 1995).

Experimental work by Assirelli (2010, Unpublished results) showed that the moisture of sorghum biomass, after a rainfall, can rise to a level higher than the moisture at cutting and reach a value close to 5 kg H_2O (kg DM)$^{-1}$, which is the same (theoretical) value reported by McGechan and Pitt (1990) for grass swaths. Based on our experimental data, we used the M_{w_max} 4.67 kg H_2O kg DM^{-1}.

Table 2.3 - Sorghum haying model parameters.

Parameter name	Value	Unit	Source
w	0.156	$(\text{mm H}_2\text{O})^{-1}$	"Calibration"
A	0.135	-	Bonner and Kenney (2013)
B	-0.0006	$(°\text{C})^{-1}$	Bonner and Kenney (2013)
C	0.425	-	Bonner and Kenney (2013)
M_{w_max}	4.67	kg H_2O (kg DM)$^{-1}$	Assirelli *et al.*, (2013)
M_{w_opt}	0.25	kg H_2O (kg DM)$^{-1}$	Bonner and Kenney (2013)
M_{wopt_max}	0.334	kg H_2O (kg DM)$^{-1}$	Assirelli *et al.*, (2013)
h_r	0.833	days	McGechan and Pitt (1990) van Elderen *et al.*, (1972)
r_{Mw}	0	-	Amaducci *et al.*, (2004)
t_{hmax}	20	days	"local experiance"
$r0, r1, r2, r3, r4$	0.00121, 0.51, 1.15, 0.069, 0.0068	-	Barr *et al.*, (1995)

The rain re-wetting rate, H_p (mm h^{-1}) is computed with:

$$H_p = p \cdot \frac{t_s}{h_r} \cdot (M_{w\_max} - M_w) \tag{2.6}$$

where p (mm h $^{-1}$) is the hourly precipitation, t_s is the model time step and h_r is the time constant for sorghum rehydration. The value of h_r was estimated via calibration and a final value of 20 h was found to work satisfactorily. Our estimate of h_r falls within the range of 15 h and 25 h used respectively by McGechan and Pitt (1990) and van Elderen *et al.*, (1972) and cited by Barr *et al.*, (1995). Re-wetting by dew was considered negligible and not included in the model.

The rate of total water loss H_t (mm h^{-1}) is the following:

$$H_t = H_r - H_p \tag{2.7}$$

Dry matter losses occurring after cutting were estimated following the computing scheme proposed by Barr *et al.*, (1995) for forage respiration. It is assumed that plant respiration only takes place in the fraction of respirable substrates and it is based on air temperature (T_a) and biomass moisture, M_w, (kg H_2O (kg DM^{-1})). The amount of degradable substrates (D, kg) was computed as a fraction r_{Mw} of the total dry biomass. A fixed value of 0.11 was adopted for r_{Mw} (Amaducci *et al.*, 2004).

$$D = W_{B0} \cdot r_{Mw} \tag{2.8}$$

where W_{B0} (kg m^{-1}) is the biomass at cutting time and r_{Mw} (%) is the fraction of easily fermentable carbohydrates contained in the sorghum biomass.

It was also assumed that respiration ceases when respirable substrates are exhausted or when biomass moisture drops below 0.27 kg H_2O (kg DM)$^{-1}$ (Barr and Brown, 1995).

The rate of biomass loss for respiration R_r (kg h^{-1}) is computed with:

$$R_r = \begin{cases} r_0 \cdot D \cdot (e^{r_1 \cdot M_w} - r_2) \cdot e^{r_3 \cdot T_a}, & T_a \leq 25\,°C \\ r_4 \cdot D \cdot (e^{r_1 \cdot M_w} - r_2) \quad , & T_a > 25\,°C \end{cases} \tag{2.9}$$

where r_0, r_1, r_2, r_3 and r_4 are empirical constants (Table 2.3).

Microbial activity causing cellulose and fibre degradation was considered negligible.

The dynamic equations for the two state variables of the model are:

$$\frac{\mathrm{d}}{\mathrm{d}t} W_B = -R_r \tag{2.10a}$$

$$\frac{\mathrm{d}}{\mathrm{d}t} W_{H_2O} = -H_t \tag{2.10b}$$

The two Equations (2.10a) and (2.10b) are integrated over time t (days) starting at time t_0:

$$t_0 = day_{cut} + h_{cut} \cdot (1/24) \tag{2.11}$$

where day_{cut} is the day of year of harvest and h_{cut} is the hour of the day. Default value for h_{cut} was 07:00h but it

could be set at different times to mimic farmers' needs and operation time. Integrations are performed with an Eulero integration scheme and the time step is 1 hour (=1 day/24). Equation (2.2) is computed at each integration step and M_w is compared with the target M_{end}. The drying process ends when:

$$M_w \leq M_{end} \tag{2.12}$$

where M_{end} is the moisture that triggers the end of the drying process:

$$M_{end} = \begin{cases} M_{w\_opt} & if\ (t_h < t_{hmax}) \\ M_w & if\ (t_h \geq t_{hmax})\ and\ (M_w \leq M_{w\_max}) \end{cases} \tag{2.13}$$

t_{hmax} (days) is the maximum time allowed for drying after harvest (cut or conditioning), and t_h (hours) is the haying time:

$$t_h = t - t_0 \tag{2.14}$$

If conditions of Equation (2.13) are not met, the haying process is considered to have failed.

An additional important feature of the model was the trigger for baling. This was set up to bale the biomass at the optimal biomass moisture content ($M_{w\_opt.}$) of ≤18%. However, using a specific "if and else" algorithm it was also possible to force baling at a moisture content > 18% but < 30% if the model detected rainfall during the subsequent days of the drying period. This feature simulates the behaviour of a farmer that, facing unfavourable weather conditions, prefers to bale sorghum at a sub-optimal moisture content rather than lengthening the field drying process and increasing the risk of a haying failure.

2.2.3 Sorghum haying model calibration and validation

The sorghum haying model was calibrated and validated with data collected in several experimental trials conducted in northern Italy. Table 2.4 provides the most relevant information to describe the calibration and validation data sets, indicating the source of each data point. Original data herein presented was obtained from field trials carried out in 2012 using medium-late sorghum genotypes (Biomass 133) grown in two experimental trials from April to October 2012 in two locations in the Po Valley: Casatisma (Pv), (45°02'58"N, 9°09'50"E, 79 m a.s.l.) and Casei Gerola (Pv) (45°02'05"N, 8°54'33"E, 81 m a.s.l.), on 0.64 ha and 0.77 ha, respectively.

Conventional tillage (30 cm deep ploughing followed by 1 passage of tandem disk harrow and 1 passages of power harrow) was performed and sowing was done on April 30th and May 8th respectively in Casatisma and Casei Gerola with a pneumatic drill (Maschio Gaspardo SP Dorata 6 rows) using 10 kg ha^{-1} (20 seeds m^{2}) with a layout of 0.70 x 0.10 m. Nitrogen fertilization (80 kg ha^{-1}) was applied once during hoeing. No irrigation was applied.

At crop maturity the sorghum was harvested using a mower conditioner prototype (Pari *et al*., 2010, Assirelli *et al*., 2013). In Casatisma 2 days after harvest, cut biomass was turned with tedding Claas Volto 800; on day 4 windrows were created with windrow turners using Claas Liner 3100 and the dry sorghum was baled on day 5 with Krone Big Pack HS 1290. The prismatic bales had weight of approximately 450 kg, dimensions of 2.2 x 1.2 x 0.7 m and volume of 1.85 m^{3}.

In Casei Gerola sorghum was turned 14 days after harvest (due to 3 consecutive days of rainfall 2 days after harvest); on day 15 dry biomass sorghum was windrowed and baled.

In the time period between harvesting and baling, daily biomass samples, were taken. Three conditioned plants were randomly taken from the field and placed in paper bags and the wet biomass weight was recorded. All samples were dried at 105° until reaching constant weight to determine the moisture content of the biomass.

The moisture content of the samples collected at harvesting is presented in Table 2.4 as the harvest moisture content. The moisture content of this and all successive samples was used to calibrate and validate the drying process.

2.2.4 Modelling

The simulations for both models (CropSyst and sorghum haying model) were conducted with an artificial climate data set of 140 years, obtained with the climate generator of the CropSyst package.

Table 2.4 - Geographical position of field trials and data regarded sorghum genotypes involved in the calibration and validation of sorghum haying model.

Field location	Longitude (°)	Latitude (°)	Elevation (m a.s.l.)	Sorghum genotype	Harvest date	Moisture at harvest (%)	Plant height (m)	Basal diameter (mm)	Plant density (N m^{2})	DM (Mg ha^{-1})	Source
Calibration											
Rivalta Scrivia (AL)	44° 50' 22''	8° 48' 46''	141	H 133	03/09/2009	72.6	3.03	16.86	12.67	18.9	Pari *et al*., 2011
Casatisma (PV)	45° 02' 58''	9° 07' 44''	77	Biomass 133	13/08/2012	75.91	2.59	23.2	13.67	17.3	*
Casatisma (PV)	45° 02' 58''	9° 07' 44''	77	Trudan HL	14/09/2012	77.97	2.41	14	10.2	15.94	*
Casatisma (PV)	45° 02' 58''	9° 07' 44''	77	Bulldozer	14/08/2012	74.27	3.77	22.6	9.86	22.1	*
Casei Gerola (PV)	45° 00' 21''	8° 55' 40'	81	Biomass 133	16/08/2012	74.19	2.32	21.2	9.35	18.17	*
Casei Gerola (PV)	45° 00' 21''	8° 55' 40'	81	Trudan HL	07/09/2012	74.87	2.47	13.3	9.12	18.14	*
Casei Gerola (PV)	45° 00' 21''	8° 55' 40'	81	Bulldozer	07/09/2012	74.06	3.37	22.3	8.77	20.01	*
Validation											
Forlimpopoli (FC)	44° 11' 20''	12° 07' 42''	31	Biomass 133	17/09/2007	72.4	3.1	28	/	11.1	Assirelli, 2010 (Unpublished results)
Mirandola (MO)	44° 53' 16''	11° 03' 47''	22	Biomass 133	29/07/2009	73.4	2.88	16.75	14	14	Pari *et al*., 2011
Apiro (MC)	43° 23' 28''	13° 07' 54''	516	Biomass 133	05/10/2007	72.5	2.7	24	/	5.92	Assirelli, 2010 (Unpublished results)
Finale Emilia (MO)	44° 49' 57''	11° 17' 28''	14	Biomass 133	18/08/2010	73	/	/	/	/	Assirelli, 2010 (Unpublished results)

* Data collected in field experimental trials carried out in two location in the Po Valley from April to October 2012.

The climate generator was fed with 39 years of data from a weather station located in Voghera (PV), in the Po Valley, Italy (44°59’29” N, 9°00’43” E, altitude 96 m a.s.l.). Any missing data were replaced with data obtained from the Joint Research Centre, JRC (Interpolated AGRI4CAST Meteorological).

With the objective to populate the results database with an extended and continuous set of harvest dates between the end of July and half September, simulations were cycled every year with a target the sowing date on 20 April (considered optimal for sorghum in northern Italy and for the interested cultivation area). The main setting parameters are listed in Table 2.5.

Table 2.5 - Management setting for CropSyst model.

Description	Value
Simulation start date	01-Gen
Simulation end date	31-Oct
Sowing date	20-Apr
Irrigation	No irrigation (rainfed)
Total Nitrogen	120 kg ha^{-1} (Urea)
Harvest sorghum	At crop maturity

To obtain realistic sowing conditions the software was set up exploiting the feature 'conditional date sowing of CropSyst'. This was done with the aim to allow sowing only in the conditions that, the 'average grower' would require for his sorghum crop: sufficient water in the top layer, trafficable soil, no significant precipitations on the sowing day and an average soil temperature above 14 °C in the top 5 cm layer.

2.2.5 Probability to exceed a determinate biomass moisture threshold and composite probability.

In order to identify the sorghum genotype that shows the highest probability to be baled with a biomass moisture content between 18% and 30%, the probability of exceedance (*Pe*) was calculated.

The probability of exceedance (*Pe*) was computed for sorghum yields for each genotype to realize probability plots (Rivington and Wallach, 2015).

Haying probability within a set of defined biomass moistures ($PH,_{m(i)}$) was computed for each genotype within the range of biomass moisture 18% - 30%:

$$PH_{m(i)} = \frac{N_{m(i)}}{N_{tot}} \tag{2.15}$$

where N_{tot} is the total number of success haying cases for a given genotype and $N_{m(i)}$ is the number of haying success cases with biomass moisture below of a given value $m_{(i)}$:

$$m_{(i)} \leq m_{(i+1)} + 0.5 \tag{2.16}$$

and

$$17.5 < m_{(i)} \leq 30 \tag{2.17}$$

Furthermore, for all genotypes, a composite probability $PC_{m(i)}$, taking into account concurrently *Pe* and *PH* probabilities was computed for two haying biomass moistures, 18% and 30% with the products:

$$PC_{18} = Pe \cdot PH_{18} \tag{2.18}$$

$$PC_{30} = Pe \cdot PH_{30} \tag{2.19}$$

where *Pe* represents the whole set of exceedance probabilities of a given genotype.

2.3 Results

2.3.1 CropSyst calibration and validation

Model performance for calibration and validation datasets are summarized by the indexes given in Table 2.6 while Fig. 2.1a and 2.1b illustrate the relation between observed (X-axis) and simulated (Y-axis) values of biomass sorghum production.

According to the 1:1 line of Fig. 2.1a and 2.1b the agreement between observed and simulated values was satisfactory, though the dimensionless statistics of *d* and *EF* families highlighted some differences between the two groups of datasets (Table 2.6).

In particular, relatively small deviations of *RMSE* (2.012 Mg DM ha^{-1} (*nRMSE* = 9.3%)) and *MAE* (1.66 Mg DM ha^{-1} (*C* = 0.076)) were found between the simulated biomass production and the calibration data, and a positive mean error *E* (0.194 Mg DM ha^{-1}) indicated that the model slightly overestimated the observed data of the calibration dataset.

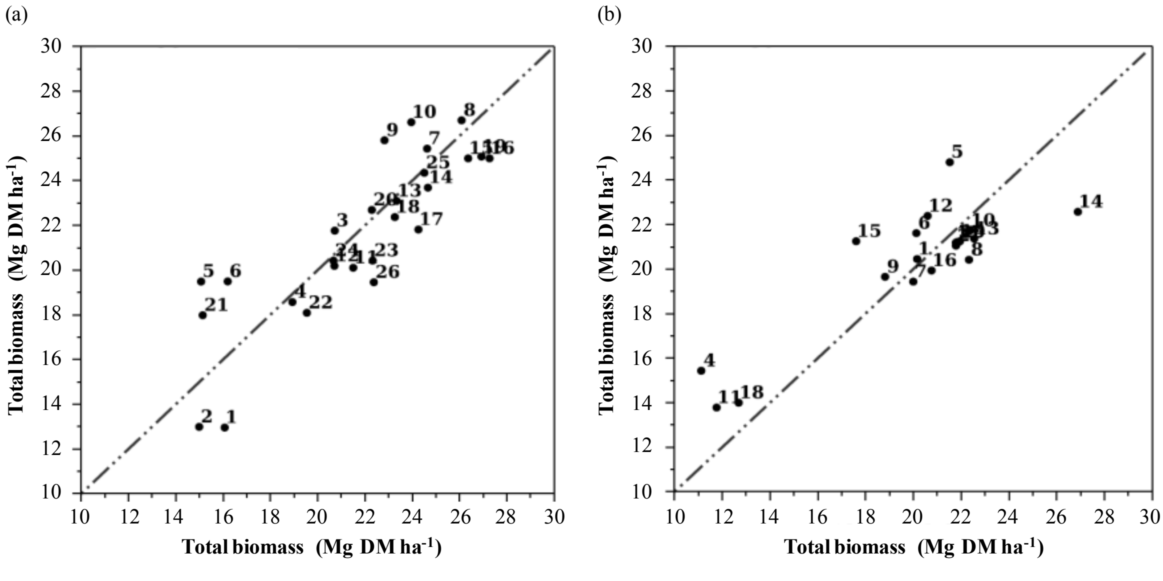


Fig. 2.1- CropSyst calibration and validation results. Comparison of observed (X-axis) and simulated (Y-axis) sorghum biomass production (Mg DM ha^{-1}) for calibration (a) and validation (b).

Table 2.6 - Statistical evaluation of CropSyst model according to Yang *et al.*, (2014).

Evaluation Index	Calibration	Validation
Mean	21.715	19.925
Sample number	26	20
RMSE	2.012	2.024
nRMSE	9.263	10.156
MAE	1.660	1.586
C	0.076	0.080
E	0.194	-0.311
EF	0.702	0.720
EF1	0.452	0.426
d	0.918	0.899
d1	0.722	0.662
d1'	0.726	0.713
CRM	0.009	-0.016

The deviations were *RMSE* = 2.023 Mg DM ha^{-1} (*nRMSE* = 10.16%), *MAE* = 1.58 Mg DM ha^{-1} (*C* = 0.079), and there was a negative value of E (-0.311 Mg DM ha^{-1}).

In the validation dataset the biomass production simulated during the growing season was underestimated compared to the observed values.

3.2 Sorghum haying model calibration and validation

Model performance for calibration and validation datasets are summarized by the indexes given in Table 2.7 while Fig. 2.2a and 2.2b illustrate the relation between observed (X-axis) and simulated (Y-axis) values of biomass moisture during the drying period, respectively for calibration and validation. According to the 1:1 line of Fig. 2.2a and 2.2b the agreement between observed and simulated values was satisfactory. Some deviations were observed from the line 1:1 in the validation data set for the highest values of moisture.

A relatively small deviation of *RMSE* (0.22 kg H_2O kg DM^{-1} (*nRMSE* = 17.6%)) and *MAE* (0.159 kg H_2O kg DM^{-1} (*C* = 0.123)) were found between the simulated biomass moisture and the calibration data and a negative mean error *E* (-0.013 kg H_2O kg DM^{-1}) indicated that the model slightly underestimated the observed data of the calibration dataset.

In the validation dataset, the biomass moisture simulated during the drying phase was overestimated compared to the observed values as revealed by a larger deviation *RMSE* (0.464 kg H_2O kg DM^{-1} (*nRMSE* = 33%)) and MAE (0.303 kg H_2O kg DM^{-1} (*C* = 0.217)). The positive value of E (0.054 kg H_2O kg DM^{-1}) indicated that the model tended to overestimate the observed values of the validation dataset.

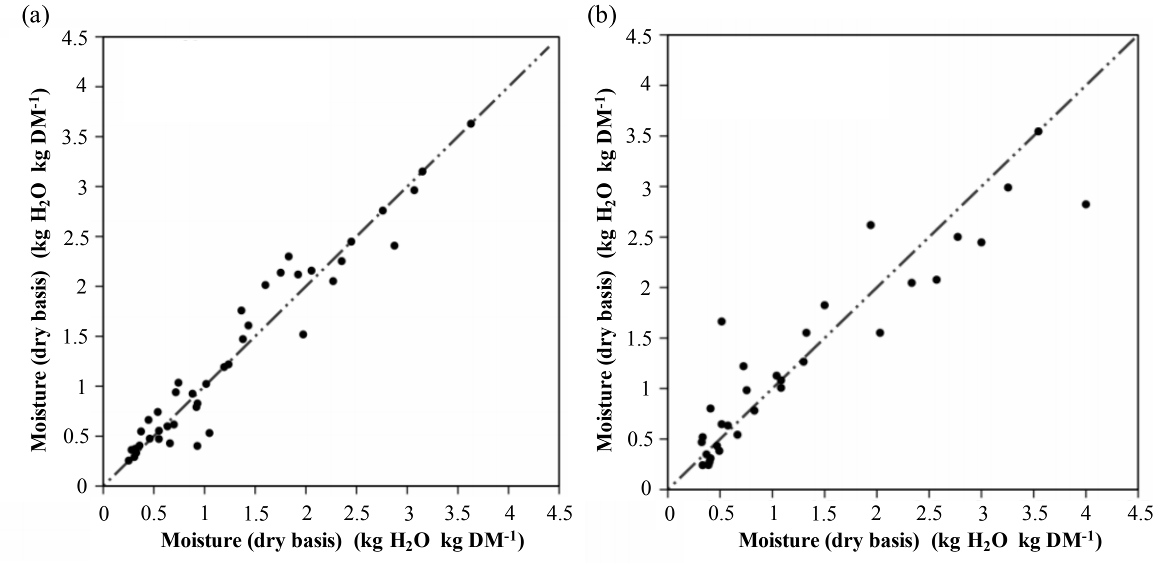


Fig. 2.2 - Sorghum haying model calibration and validation results. Comparison of observed (X-axis) and simulated (Y-axis) sorghum biomass moisture content (kg H_2O kg DM^{-1}) for calibration (a) and validation (b).

Table 2.7 - Statistical evaluation of "sorghum haying model" according to Yang *et al*., (2014).

Evaluation Index	Calibration	Validation
Mean (moisture, dry basis)	1.291	1.399
Sample number	42	33
RMSE	0.228	0.464
nRMSE	17.658	33.159
MAE	0.159	0.303
C	0.123	0.217
E	-0.013	0.054
Paired-t	-0.055	0.116
$p(t \leq t_o)$ *two tails*	0.956	1.091
EF	0.937	0.855
EF1	0.790	0.696
d	0.984	0.954
d1	0.897	0.833
d1'	0.895	0.848
CRM	-0.010	0.039

A relatively small deviation of *RMSE* (0.22 kg H_2O kg DM^{-1} (*nRMSE* = 17.6%)) and *MAE* (0.159 kg H_2O kg DM^{-1} (*C* = 0.123)) were found between the simulated biomass moisture and the calibration data and a negative mean error *E* (-0.013 kg H_2O kg DM^{-1}) indicated that the model slightly underestimated the observed data of the calibration dataset.

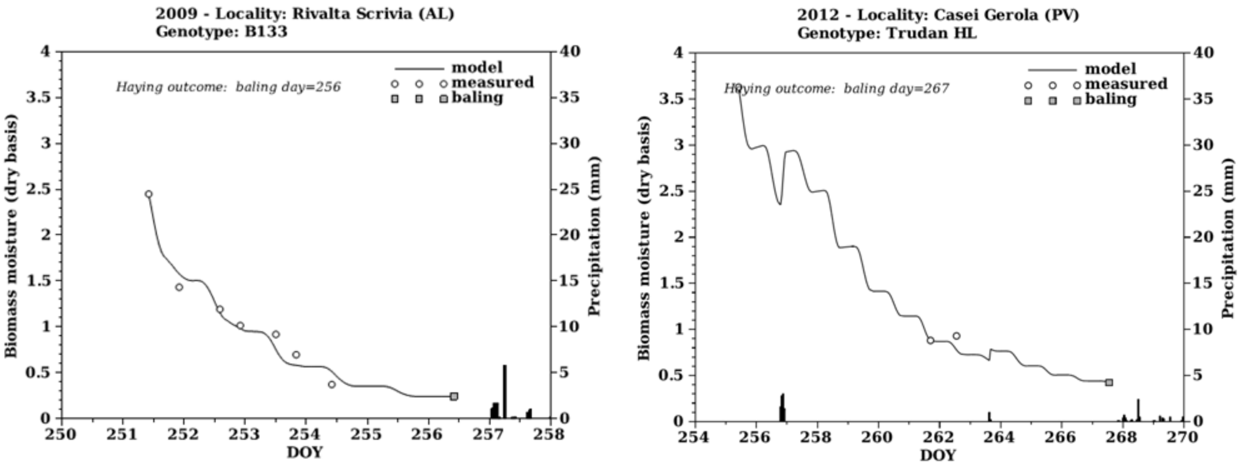
In the validation dataset, the biomass moisture simulated during the drying phase was overestimated compared to the observed values as revealed by a larger deviation *RMSE* (0.464 kg H_2O kg DM^{-1} (*nRMSE* = 33%)) and MAE (0.303 kg H_2O kg DM^{-1} (*C* = 0.217)). The positive value of E (0.054 kg

H_2O kg DM^{-1}) indicated that the model tended to overestimate the observed values of the validation dataset. The dimensionless statistics of *d* and *EF* families highlighted some differences between the two groups of datasets. The values of the efficiency indexes were slightly better for the calibration dataset, however, also for the validation dataset, indices d = 0.954 and EF = 0.855 revealed a satisfactory performance of the haying model.

Fig. 2.3 and Fig. 2.4 present respectively the calibration and validation data sets of the drying process of cut sorghum as simulated (continuous line) and observed values (white dots).

The gray square represents the final moisture (dry basis) and the time of baling. Several data sets representing different sampling times and sorghum varieties were used for model validation. The comparison between simulated and observed values for calibration and validation was performed by selecting simulated values at the times (hour of the day) closest to those of the observed data. The average time to reach a suitable biomass moisture for baling ≤ 0.22 kg H_2O (kg DM)$^{-1}$, dry basis (or ≤ 18%$_{wb}$) ranged from 4 to 18 days. The shortest drying periods were observed when there was no rain during the drying period and mean daily temperature > 20 °C, and when there was a low biomass yield. The longest drying periods were observed when rain caused re-wetting of the cut sorghum (Fig. 2.3 and Fig. 2.4). Failure to reach a suitable biomass moisture for bailing, both in simulated and observed data, occurred in Casei Gerola (PV) in 2012 with the genotype Biomass 133 due to a prolonged period of rain post harvest.

When there was no rain during the drying period it could be seen that the rate of drying gradually decreased as the biomass moisture approached ≤ 0.22 kg H_2O kg DM^{-1}, dry basis (Fig. 2.3 and Fig. 2.4).



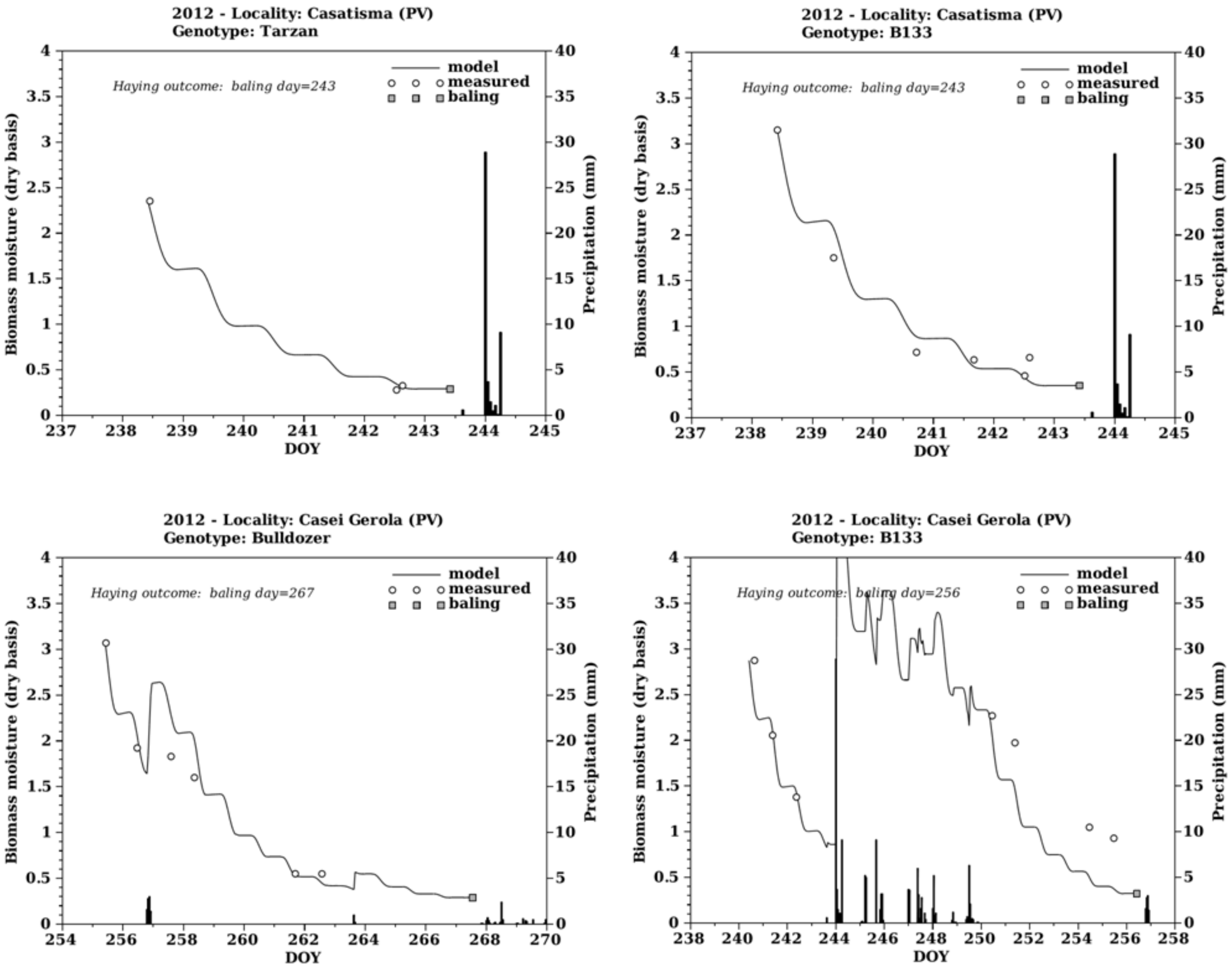
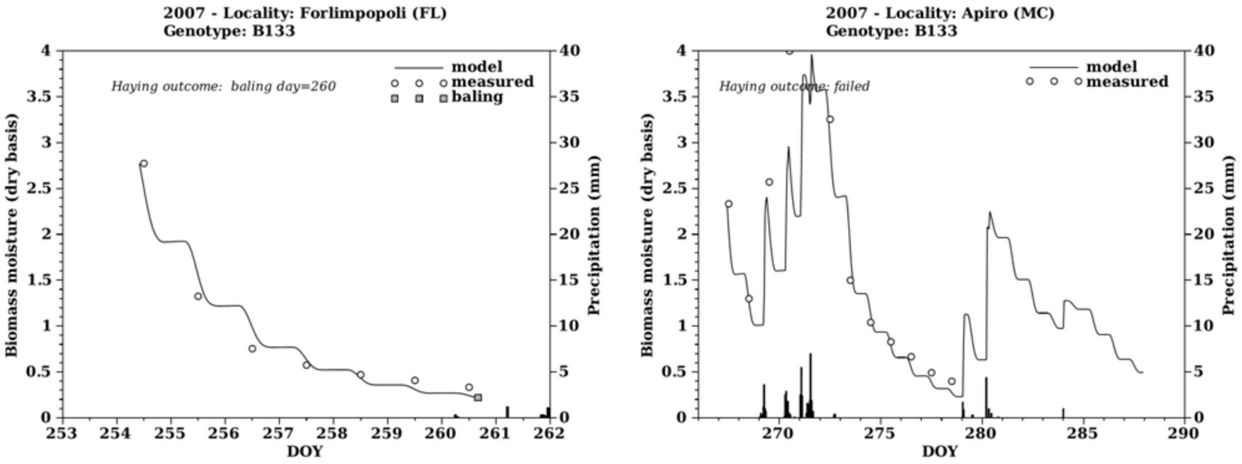


Fig. 2.3 - Sorghum haying model calibration. Observed and simulated moisture content (dry basis) of sorghum during biomass field drying process.



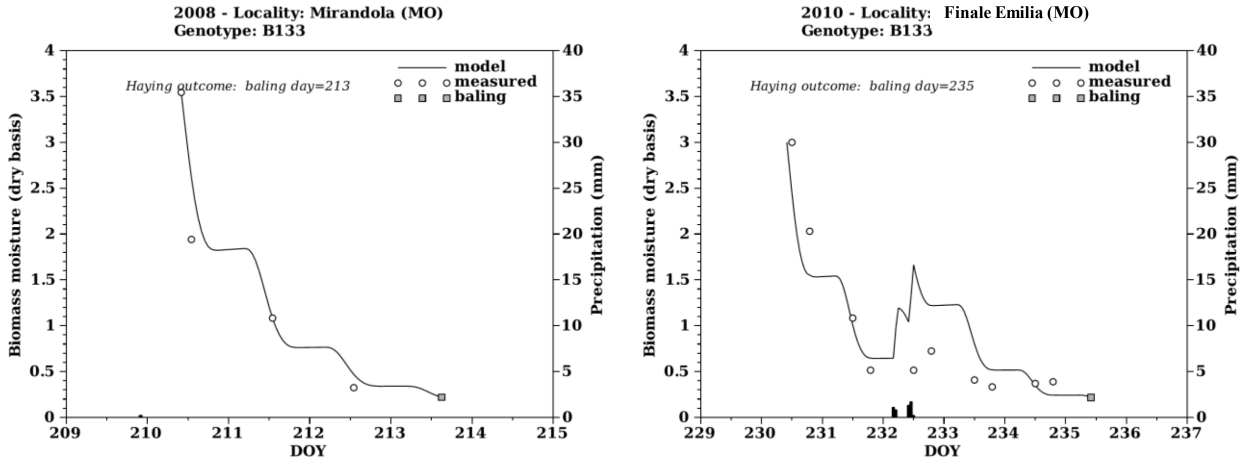


Fig. 2.4 - Sorghum haying model validation. Observed and simulated moisture content (dry basis) of sorghum during biomass field drying process.

In addition, biomass moisture decreased steadily during the day, at a rate related to air temperature and humidity, while no drying occurred at night-time (flattening of the solid line (model) in Fig. 2.3 and Fig. 2.4). The flattening also reflects the assumption that overnight re-wetting of the biomass was negligible.

2.3.3 Harvest and haying

Harvesting was carried out at crop maturity, and was determined by CropSyst as the number of growing degree days-GDD (thermal units) needed to reach the phenological stage of dough maturity.

Baling date was generated by the sorghum haying model according to Equation (2.12), $M_w \leq M_{end}$ where M_{end} is a function of M_{w_opt}, which was set at 0.22 kg H_2O (kg DM)$^{-1}$ (or 18% $_{wb}$) and it was expressed as DOY. However, due to the feature of the model to force baling the haying dates generated also refer to baling done before reaching the condition of M_{w_opt}; in this case the model parameters enabled baling to occur at M_w of between 19 and 30% on a dry matter basis.

For the early, medium-late and late genotypes, the mean DOY and date and standard deviation for both the harvest and haying are reported in Table 2.8.

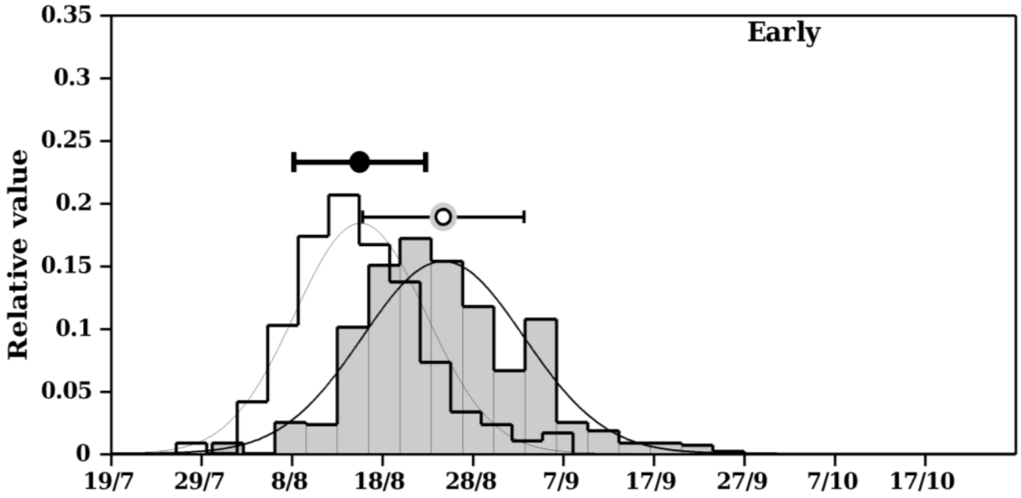
The full range of harvest and haying dates are shown in Fig. 2.5; their frequency has a symmetrical distribution, as highlighted by the superimposed continuous-dotted lines of the standard distribution. The average harvest dates were 14/8, 28/8 and 9/9 respectively for early, medium and late genotypes while the average baling dates were 23/8, 8/9 and 23/9 respectively. The difference in the number of days between the mean harvest date and mean baling date gives the mean haying period, as reported in Table 2.8; the early genotype has the shortest haying period (9.2 days) followed by the medium-late (10.9 days) and late genotype (13.6 days).

Table 2.8 - Simulated results regarding the harvest and haying date of the three sorghum genotypes considering in this study.

Distribution	Parameters	Genotype		
		Early	Medium-late	Late
Harvest date	date (mean)	14/8	28/8	9/9
	mean (DOY)	227.45	241.4	253.7
	standard deviation (days)	7.28	7.92	7.62
	Normal Dist., goodness of fit (c2 test)	7.23	13.46	12.76
Haying date	date (mean)	23/8	8/9	23/9
	mean (DOY)	236.6	252.26	267.26
	standard deviation (days)	8.94	10.28	10.47
	Normal Dist., goodness of fit (c2 test)	7.24	5.06	4.42
	mean haying period (days)	9.15	10.86	13.56

The net yield of dried baled biomass (Fig. 2.6) was calculated for each genotype by adjusting the total biomass production for mechanical and respiration losses. Mechanical losses at harvest were assumed in accordance to Assirelli (2010, Unpublished results) to be equal to 7%, while respiration losses during on-field drying varied according to the atmospheric conditions and were on average 16.6%. The average loss of biomass was therefore 23.6%. In Fig. 2.6 the boxes therefore indicate the upper and lower limits of the productive range; it can be clearly seen that medium-late and late genotypes have a wider production range than early genotypes, but mean yield of dried baled biomass did not differ greatly among genotypes, being 15.1, 15.4 and 16.5 Mg DM ha^{-1} for early, medium-late and late genotypes, respectively.

If the moisture content at which baling was performed is plotted in a box plot (Fig. 2.7a) it can be clearly seen that the early genotype was baled within a limited moisture range, while the range in biomass moisture at baling got wider with later genotypes.



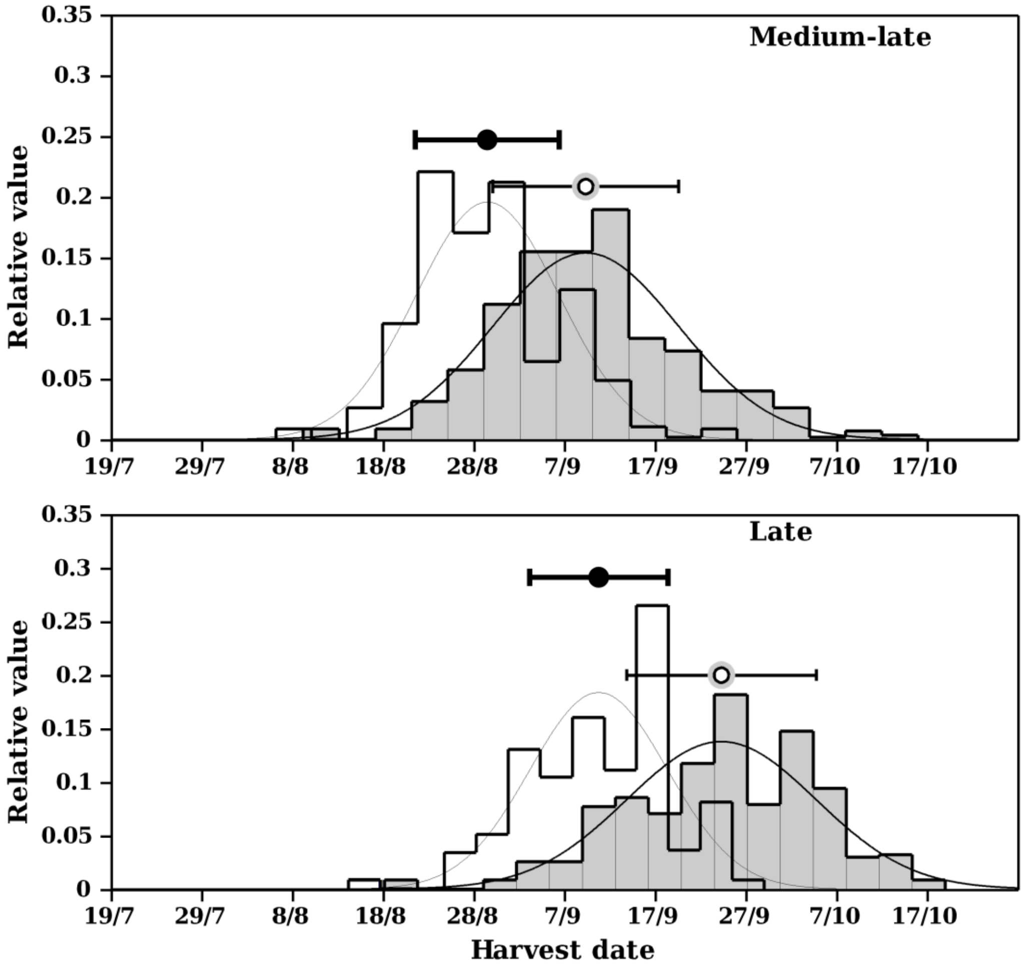


Fig. 2.5 - Relative frequencies of the simulated harvest dates (crop cutting, black line) and baling dates (gray histograms) for three sorghum genotypes with different maturity earliness. The superimposed dotted lines represent a theoretical normal distribution with mean and standard deviation of the observed data.

If the moisture content at which baling was performed is plotted in a box plot (Fig. 2.7a) it can be clearly seen that the early genotype was baled within a limited moisture range, while the range in biomass moisture at baling got wider with later genotypes.

The mean moisture at baling however, was less affected by genotype earliness, with values of 20%, 20.5% and 21.3% respectively for the three genotypes (black triangles, Fig. 2.7a). It should be remembered however, that these data only refer to simulations in which haying was successful, and it thus excludes all simulations in which haying was considered to have failed (conditions of equation 10 were not met).

Therefore, using the results of all simulations (successful haying and failed haying) it was possible to calculate, for each genotype, the probability that the biomass will dry to reach a moisture content of ≤ 30%. The results are shown in Fig. 2.7b; overall the early genotype has a greater probability of reaching a suitable biomass moisture content for baling.

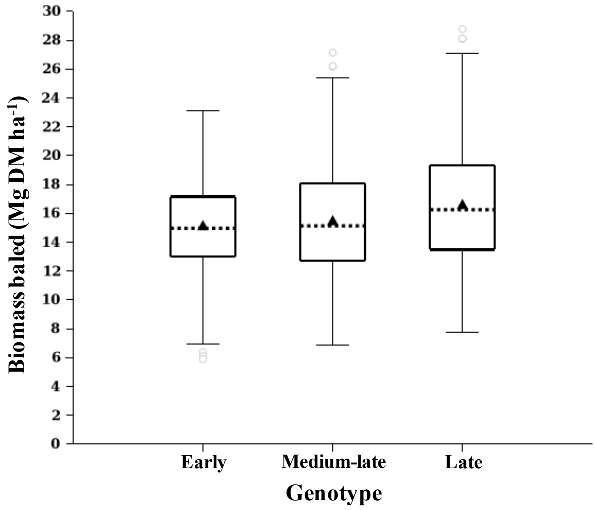


Fig. 2.6 - Simulated yields for three genotypes with different maturity earliness. The boxes have lines at the lower Q1 and upper quartile Q3 and the median values Q2 (middle horizontal lines). The whiskers (vertical lines) are lines extending from each end of the boxes to show the extent of the rest of the data. The maximum length of the whiskers is determined by 1.5 (Q3–Q1). Outliers (black circles) are data with values beyond the ends of the whiskers.

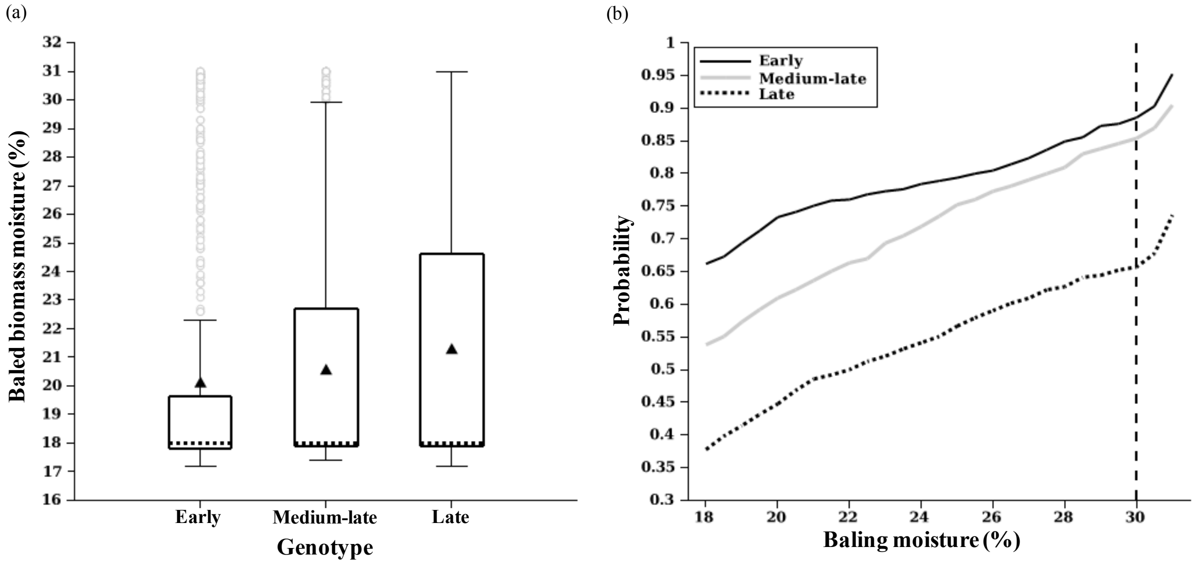


Fig. 2.7 - Biomass moisture simulation results. (a) Box plot of the biomass moisture content (%) of baled yields for three genotypes with different maturity earliness. The boxes have lines at the lower Q1 and upper quartile Q3 and the median values Q2 (middle horizontal lines). The whiskers (vertical lines) are lines extending from each end of the boxes to show the extent of the rest of the data. The maximum length of the whiskers is determined by 1.5 (Q3–Q1). Outliers (black circles) are data with values beyond the ends of the whiskers. (b) Probability to reach a moisture content of baled biomass for three genotypes with different earliness.

If targeting a 30% moisture content the probability of successfully bailing the biomass was relatively high for all genotypes; 0.88, 0.85 and 0.64 respectively for early, medium-late and late genotypes. If targeting the optimal moisture level (18%), the probability of successfully bailing the sorghum was respectively 0.66, 0.53 and 0.37.

Fig. 2.8a and 2.8b show the results of the calculation of the composite exceedance probability of a given production (abscissa) with a set humidity of the biomass.

The calculation was performed for the two reference moistures ≤ 18% and ≤ 30%. The composite probability takes simultaneously into account the probability to exceed a given production below a fixed moisture and the associated haying probability. It summarizes in a single value the probability of successfully bailing a given amount of biomass at the lower and upper limit of the moisture range used in this paper. For both reference moistures, Fig. 2.8a and 2.8b, the early genotype showed higher probabilities of exceedance for biomass yields up to 16 Mg ha^{-1} while, for higher yields a greater probability of exceedance was showed by the late genotype.

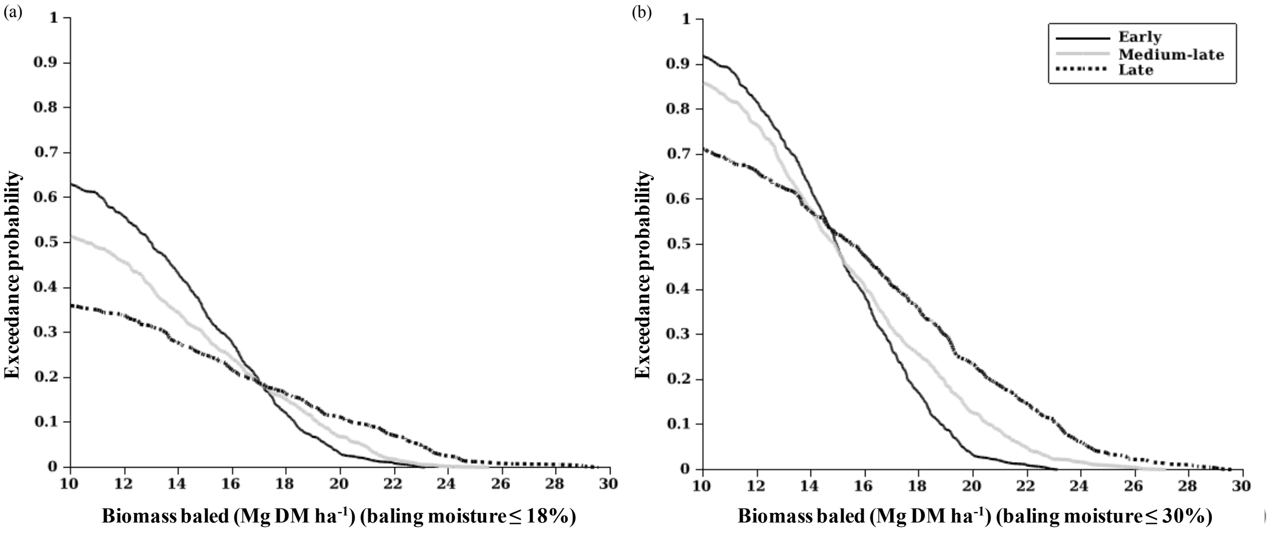


Fig. 2.8 - Composite probability of exceedance of baled yields at two moisture contents ≤ 18% (a) and ≤ 30 % (b) obtained by multiplying total probability of exceedance by the respective haying success probability (values of Fig. 2.7b).

2.4 Discussions

A physical haying model for biomass sorghum was developed in order to simulate the dynamics of moisture and respiration loss during field drying process. The destination of sorghum biomass as feedstock for energy production (direct combustion) makes qualitative aspects addressed in haying models developed for fodder production (Gupta *et al.*, 1990, Barr and Brown, 1995) less relevant.

The development of this model found a strong theoretical basis on the work of Bonner and Kenney (2013) who provided the physical background to simulate equilibrium moisture as affected by air humidity and temperature. However, the considerable thickness of sorghum stalks (Lardy and Anderson, 2003) suggests that a straightforward application of approaches as used for forage crops should be adopted with care. Bonner and Kenney (2012) compared the drying of sorghum with that of maize rather than other forage crops, which tend to have much higher rates of water loss. Despite the conditioning treatment carried out at harvest with an innovative machinery (Assirelli *et al.*, 2013, Bentini and Martelli, 2013, Rocateli *et al.*, 2013) the optimal moisture content for baling was never reached in less than 4 days. The output of the sorghum haying model shown in Fig. 2.3 and Fig. 2.4 is in agreement with the data obtained in field haying trials by other authors (Pari *et al.*, 2010, Mercer *et al.*, 2011 Rocateli *et al.*, 2013), who found that sorghum biomass could never reach a relative humidity suitable for bailing in less than 6 days after mowing. Shorter drying times to reach the critical humidity for bailing were found by Bentini and Martelli (2013) who reported that adequate moisture level for storage could be reached in two or three days in the Po Valley; in controlled conditions (growth chambers or convection ovens, where evaporation can be considered nearly uniform) thin layers of conditioned biomass dried in 16 hours at 50 °C according to Mercer *et al.*, 2011, and from 30 to 50 hours in the range of 20-30 °C respectively, according to Bonner and Kenney (2012).

It should be noted that the rates simulated by the sorghum haying model never matched the drying rates found in controlled conditions (Bonner and Kenney, 2012) because even when swaths are well distributed on the field the biomass density (kg DM m^{-2}) is very high, > 1.5 kg m^{-2} in most cases (approximately 3-5 folds higher than the density of forage crops 0.4-0.5 kg m^{-2}, Atzema, 1992) and swaths do not dry uniformly, but rather progressively from top to bottom.

In this work, the largest differences between observed and simulated data were found in correspondence with rain re-wetting the biomass in the swath. This is probably a consequence of the lack of a specific state variable (in addition to W_{H20} that simulates the water retained by the tissues) simulating the surface water retained by the matrix biomass, as was proposed by Barr and Brown (1995). The choice to reduce the state variables was imposed by the limited experimental information relative to the rewetting phase; in the future the model performance could be enhanced if a specific state variable for the water retained by the tissues could be implemented.

In contrast to that proposed by Atzema (1992) and Barr and Brown (1995) who operated a specific modification of the Penman-Monteith equation (specifically, aerodynamic and crop resistances, r_a and r_c), in our model the calculation of moisture loss, during field drying process, was based on the use of 'native' reference ET_h, assuming that the biomass loses moisture at an evapotranspiration rate that is proportional to the difference between its actual and equilibrium humidity (Equation 2.3).

In this work the extensive climate dataset generated by ClimGen (Abraha and Savage, 2006, Bal *et al.*, 2008, Laux *et al.*, 2010) produced a broad variability of harvest dates, which gave rise to a wide range of timing and climatic conditions to simulate the haying process. This enabled a clear separation of the productive features of the three genotypes which, in turn, has highlighted the role of harvest date on the success of the haying process. This result has major practical implications, in fact the highest productions of biomass sorghum are obtained with late genotypes, however, as highlighted by Quaranta *et al.*, (2010), the higher yields obtained with the late genotypes do not take into account any loss caused by haying failures, which, as shown in this paper occur more often at late harvests because the climatic conditions become progressively less favourable for field drying. Haymaking failure were also reported by Mercer *et al.*, (2011).

From a management point of view, higher probability of having excess moisture at baling with late genotypes, Fig. 2.7a and 2.7b, is a consequence of two concurrent factors:

1) most harvests are made after the end of August when the evaporating power of the atmosphere tends to gradually decrease;

2) increased chances of rainfall events after harvest lengthen the drying period and render it necessary to bale biomass in conditions of incomplete drying.

The 30% moisture upper-threshold and the feature of the model to force baling before reaching the optimal moisture content was in fact introduced to mimic the reality of baling at sub-optimal moisture content, particularly in the imminence of a rainy event. A relatively high moisture content does not hamper baling when powerful and efficient machinery is used but it shortens storage time as it favors the growth of molds, reduces biomass quality (dry matter loss and degradation of soluble and structural sugars, Bonner and Kenney, 2013, Chen and Danao, 2015) and, in extreme cases, can result in self combustion (Lemus, 2009).

From the perspective of managing sorghum for combustion in an industrial plant it should also be noted that, in addition to the problems that can arise during storage of wet biomass, there is a direct effect on the energy efficiency of the combustion process due to the influence water has on the heating value of biomass (Vargas-Moreno et al., 2012). The problem could be partially bypassed by means of biomass drying before combustion (Widell, 2013) but, in any case, this affects both plant energy efficiency and farmer economical return.

2.5 Conclusions

A sorghum haying model was developed to predict the duration and the dynamics of field drying of sorghum biomass using genotypes of different earliness. In a long term simulation study, where the crop growth model CropSyst was coupled to a sorghum haying model, the early genotype provided the best trade-off between crop yield, biomass losses and moisture content at baling. The late sorghum genotype reached the highest biomass production level (16.5 Mg ha^{-1}) but the early genotype had the highest probability of being baled at a moisture content of ≤ 18%, and it had the shortest haymaking period and lowest incidence of haymaking failures.

A further advantage of the early genotype is its earlier harvest (from 10 to 20 days before the medium-late and late sorghum genotype respectively) which leaves more time to prepare the field for the next crop in rotation.

The sorghum haying model, in combination with CropSyst, is a useful tool to explore the risk related to the cultivation of sorghum to produce a target amount of biomass to feed a power plant but also a biorefinery in which dry biomass is needed.

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CHAPTER 3

Biomass sorghum risk assessment analysis: a case study on electricity production in the Po Valley

The chapter is submitted as:
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Biomass sorghum risk assessment analysis: a case study on electricity production in the Po Valley

Abstract

The risk associated to the production of biomass sorghum (*Sorghum bicolor* (L.) Moench) to feed a power plant in the Po Valley was studied with a modelling approach. Available biomass was modelled by CropSyst, coupled to a “sorghum haying model”, using three sorghum genotypes, of contrasting earliness (early, medium-late and late), on a mosaic of virtual farms created in the target cropping area. The energy performance, from cradle to farm gate, of the biomass production system was performed calculating Energy Return on Investment (EROI), Net Energy Gain (NEG) and Energy Use Efficiency (EUE).

The highest baled biomass (14.04 Mg DM $ha^{-1}y^{-1}$) was obtained with the early genotype that had less haymaking failures (6.9%), followed by the late and medium-late genotypes. As a consequence, the early genotype showed the highest probability to exceed the biomass needs of the power plant considering a target cropping area of 4221.6 ha. The early genotype showed the highest EROI (14.8), NEG (205.6 GJ $ha^{-1}y^{-1}$) and the lower EUE (1.06 GJ Mg^{-1} DM y^{-1}).

To achieve the 0.5 probability to exceed the target biomass production the cultivation with the early, medium-late and late genotypes should be carried out on 4557.9, 5159.6 and 4961.6 ha, respectively.

Keywords: *Sorghum bicolour*, energy crops, risk assessment analysis, dry matter production, energy balance, EROI, NEG, EUE

3.1 Introduction

As indicated in the Renewable Energy Directive (EU-RED, 2009), Europe considers the Renewable Energy Sources (RES) able to reduce fossil energy consumptions and greenhouse gas (GHG) emissions (Harmsen *et al*., 2011). In this frame, biomass is considered an important source of bioenergy (Sims *et al*., 2006), biomaterials and chemicals (Cherubini, 2010) and is also a promising and interesting energy source to mitigate greenhouse gas emissions (Cherubini *et al*., 2009, Creutzig *et al*., 2014).

However, biomass production for energy purposes has some implications and risks that can negatively affect the sustainability of the entire bioenergy system (Popp *et al*., 2014).

In order to identify the potential constraints involved in a bioenergy production system, the development of a risk assessment analysis is necessary to provide a practical management tool for policy makers, planners and the bioenergy industries and thus support policy development and bioenergy deployment at different scales (Elghali *et al*., 2007).

Risk assessment analysis involves various disciplines such as engineering methodologies, ecology, physics, psychology, statistics, sociology, chemistry, economics and toxicology.

In scientific literature there are some studies regarding the risk assessment analysis on climate change impact on crops yield (Jones, 2001, Li *et al*., 2009, Langholz *et al*., 2014), on pesticide seeping into surface water (Solomon *et al*., 1996), on use of genetically modified organisms (GMO) into the environment (Wolt *et al*., 2010), and on the evaluation of bioenergy systems sustainability (Elghali *et al*., 2007).

In this study a risk assessment analysis was performed to explore the main constrains related to the cultivation of biomass sorghum (*Sorghum bicolor* (L.) Moench) and identify management options to feed a power plant in the Po Valley (Northeast of Italy) with sorghum biomass.

Sorghum is an annual C4 herbaceous crop that can be used as a dedicated ligno-cellulosic energy crop in energy production (Rooney *et al.,* 2007, Amatya *et al*., 2014, Gill *et al*., 2014), namely anaerobic digestion, second generation bioethanol production (Amaducci *et al*., 2000, Davila-Gomez *et al*., 2011, Zagada-Lizarazu and Monti, 2012, Agostini *et al*., 2015), and to generate electricity by direct combustion (Zagada-Lizarazu and Monti, 2012).

The use of sorghum for bioenergy purposes (i.e. to generate electricity by direct combustion) should take into consideration two aspects: (I) the choice of the correct genotype and (II) the suitable harvest technology; the combination of these two factors is essential to optimize the field drying process, required to decrease the high moisture content at time of harvest (Quaranta *et al*., 2010, Pari *et al*., 2011, Zagada-Lizarazu and Monti, 2012, Assirelli *et al*., 2013). In a modelling study to compare three sorghum genotypes of contrasting earliness (see Chapter 2) showed that the best trade-off between biomass production and biomass moisture content at the time of baling was provided by the earliest genotype. In addition an early genotype, requiring a lower duration of the field drying process, reduce the exposition of the biomass at adverse weather conditions that can occur after harvesting (see Chapter 2). For this reason to reduce the risk of crop failure and to guarantee the coverage of biomass power plant needs, the use of an early sorghum genotype is preferable; yet on the other hand, a late genotype is likely to yield a higher biomass production (Quaranta *et al*., 2010) even if the risk of crop failure is higher than a early and a medium-late genotype.

Achieving an high biomass baled available to combustion at biomass power plant is essential also to obtain a positive energy balance and an economically profitable production (Jørgensen, 2011).

The identification of the energy input and output involved in a bioenergy system, is fundamental to quantify the sustainability of the entire biomass supply chain, as reported by Arodudu *et al*., 2013, who suggested to use energy-based indices as measures of bioenergy system performance.

A simplified energy balance, from cradle to farm gate (Djomo *et al*., 2011) was carried out, in this study, to quantify the energy input and output involved in the biomass sorghum supply chain and to calculated three energy bases index as Energy Return on Investment (EROI) defined as the ratio between the amount of energy produced (expected return) and the non-renewable primary energy needed to produce it (investment) (Hall *et al*., 2009), Net Energy Gain (NEG) defined as the gained difference in energy between the gross energy output produced (i.e., the energy content of the biomass at the farm gate) by the bioenergy system, and the total energy invested to obtain it (i.e., the fossil energy input) (Hill *et al.*, 2006) and Energy Use Efficiency (EUE) defined as the energy requirement to produce a certain quantity of dry matter (Monti and Venturi, 2003).

The main purpose of this work was to carry out a risk assessment analysis with the followed objectives: (I) to estimate the acreage necessary to plant sorghum to cover 70% (or 64000 Mg DM y^{-1}) of the needs of a biomass power plant in the Po Valley and (II) to compare the biomass production and energetic performance of three sorghum genotypes with different earliness (early, medium-late and late) in order to determine the probability of different genotypes to exceed 70% (or 64000 Mg DM y^{-1}) of the power plant needs.

3.2 Materials and Methods

3.2.1 Description of the case study

This work was commissioned by the Lombardy Region as part of a feasibility study to convert a sugar factory, that was closed in accordance to the 2006 European Reform of sugar Common Market Organization (320/2006/EC), to a biomass power plant. Farmer associations in agreement with the Lombardy Region imposed the constraint that the power plant should operate on feedstock produced or recovered on farm, within the ex-sugar factory supply area. In particular it was agreed that 70% of power plant needs would be covered by dedicated biomass sorghum cultivations.

It was calculated that to satisfy 70% of the needs of the power plant, characterized by a thermal capacity of 15 MW_{el} (50 MW_{th}), 64000 Mg DM $y^{-1}$of sorghum (LHV_{dry} 15.7 MJ kg^{-1}) would be needed.

The study aimed at exploring the production risk and the energy performance of biomass sorghum cultivated to satisfy the abovementioned power plant feedstock needs. Main objective of the study was the calculation of a reference cropping area to be planted annually with sorghum and the probability to exceed the power plant needs with the biomass baled on this target cropping area. The energy performance was assessed calculating the Energy Return on Investment (EROI), Net Energy Gain (NEG) and the Energy Use Efficiency (EUE) along the whole production system with an approach from cradle to farm gate.

3.2.2 Risk assessment

The risk assessment analysis, whose structure is represented in Fig. 3.1, was performed according to the following list of actions:

1) Calculation of the target cropping area to be cultivated annually with sorghum, based on power plant needs and average biomass sorghum baled per hectare;

2) Creation of a mosaic of virtual farms, distributed in the biomass sorghum supply area, to support a long-term simulation (39 years) of biomass sorghum production;
3) Calculation of actual baled sorghum production in the biomass supply area using the CropSyst model (Stöckle *et al*., 2003) coupled to the "sorghum haying model" developed in this thesis (Chapter 2), and simulating the use of three sorghum genotypes of contrasting earliness (early, medium-late and late);
4) Quantification of the probability to exceed 70% (or 64000 Mg DM y^{-1}) of total power plant needs using sorghum biomass, quantified using the data generated in a long-term (39 years) simulation where three sorghum genotypes were cultivated in the mosaic of virtual farms.

Action 1) To calculate the target cropping area to be planted annually with sorghum, the amount of sorghum biomass needed to cover the power plant needs (64000 Mg y^{-1}) was divided by the average biomass production of a medium-late sorghum genotype (Biomass 133 commercialized by Syngenta) tested in a multi-location experiment conducted in 2010 in the catchment area of the power plant as described in Chapter 2.

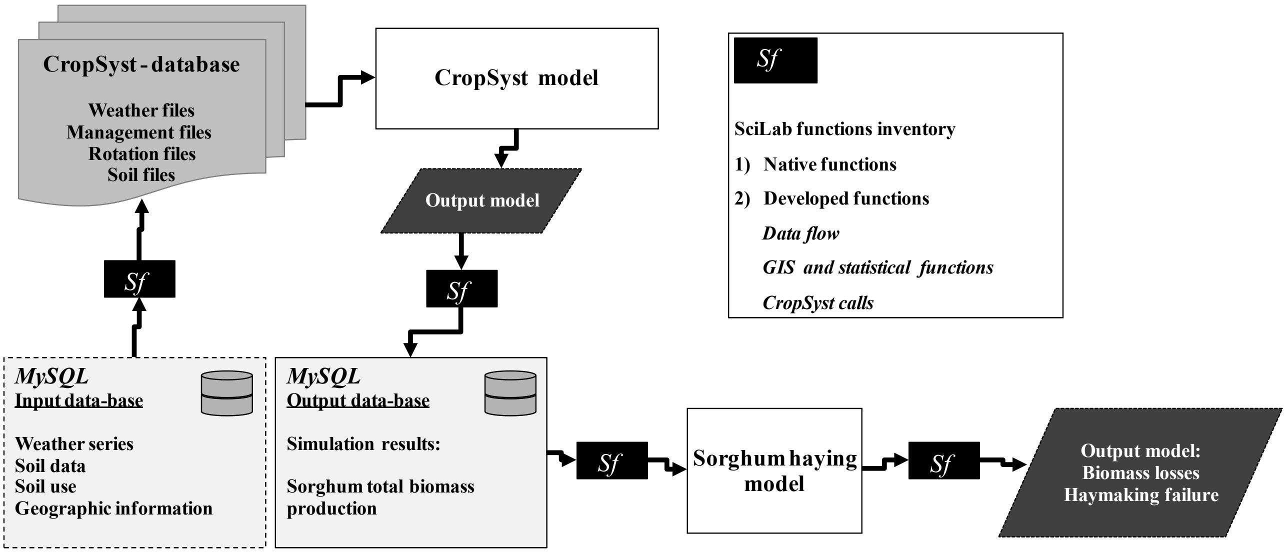


Fig. 3.1 - Schematic representation of the framework structure used in this study to perform the risk assessment analysis. This structure was based on two models: (I) CropSyst model to simulate long-term biomass sorghum production; (II) "sorghum haying model" to simulated biomass losses and haymaking failure.

Action 2) To support long-term modelling of sorghum biomass production, a mosaic of virtual farms geo-referenced in the catchment area of the power plant was created in a three steps process: a) determination of farm size; b) estimation of the proportion of land cultivated with sorghum in each farm; c) farms distribution in the catchment area of the power plant (Fig. 3.2).

a) Statistical information on farm size in the study area was obtained from the Italian Institute for Statistics (ISTAT). ISTAT data revealed an asymmetry in farm size distribution with a peak between 7 and 10 ha, and a wide range of frequency for larger farms (X-Y ha). To model a realistic distribution of farm sizes, a population of farms i was modelled by sampling values from a gamma distribution with *shape=3* and *scale*=0.125 and each farm was characterized by a total farm area Fa_i (ha). The *shape* and *scale* of the parameters were chosen to generate sample values consistent with the distribution of ISTAT data. The farm shape arbitrarily assigned to the farms was a rectangle with a ratio $\boldsymbol{q}$, randomly generated, between major and minor sides, $\boldsymbol{l_m}$ and $\boldsymbol{l_n}$:

$$q = \frac{l_\mathrm{m}}{l_\mathrm{n}};\ 2 < q < 10 \tag{3.1}$$

b) The fraction $\boldsymbol{f_r}$ of arable land in each farm to be cultivated with sorghum was derived from a survey carried out in 2010 with 20 farmers involved in the sorghum field trials (Chapter 2). Assuming that the maximum number of crops grown annually in a farm is three, the fraction $\boldsymbol{f_r}$ of land dedicated to sorghum was set equal to 1/3.

c) It was assumed that the virtual farms were equally distributed around two focus centres: the biomass power plant (45°00'N, 8°54'E) and a satellite storage facility (SSF), where biomass is temporarily stored before being transported to the power plant, were located 25 km from the power plant (45°08'N, 9°21'E). The position of each virtual farm was computed using polar coordinates: r (m) was the distance from the plant or storage centre; α (degrees to North) was the polar angle. The r distance was sampled from a normal distribution (Scilab, function grand, with mean=0 and standard deviation=30000 m), while α was computed with a random number generator (Scilab, function rand). Polar coordinates were successively transformed into Cartesian coordinates and implemented into a geographical information system as EPSG 3857 coordinates for maps visualization. To optimise the position of the virtual farms, discarding localisation on roads, rivers, urbanised places, vineyards, orchards and paddy rice fields a thematic map (roads, buildings, rivers, etc.) and a soil land use maps, provided by ERSAF (Regional Agency for Agriculture and Forests, Lombardy Region) were used (Table 3.1). The record of each selected farm was completed with the additional information on soil type and weather station. Meteorological data, land use and soil maps were stored on a MySQL relational data-base. Daily meteorological data were provided by I.T.A.S. (Carlo Gallini Voghera, Lombardy Region) and from the Joint Research Centre's (JRC) Crop Growth Monitoring System (CGMS) meteorological database (Micale and Genovese, 2004) which contains meteorological parameters from weather stations interpolated on a 25x25 km grid (1975-2014). Automation of calculation, data flow management and statistics were performed by using Scilab scripts (Version 5.4.1

Scilab Enterprises and Consortium Scilab, 2012). The creation of virtual farms was stopped when the cumulated biomass Y_c (Mg y^{-1}) reached the theoretical target biomass for total sorghum yields, Y_t = 64000 Mg y^{-1}, that was estimated to cover the biomass power plant needs from biomass sorghum. The cumulated biomass Y_c (Mg y^{-1}) is calculated as follows:

$$Y_c = \sum_{i=1}^{n} Fa_i \cdot f_r \cdot Y_m \cdot h_L \tag{3.2}$$

where Y_m (Mg ha^{-1} y^{-1}) is the mean biomass yield observed in previous experiment (Chapter 2), and h_L is the mechanical losses (Mg ha^{-1} y^{-1}) set equal to 7%, in accordance to Assirelli (2010, Unpublished results), of cut biomass at time of harvest and *n* is the number of virtual farms which was incremented of one unit till reaching the final number N_f.

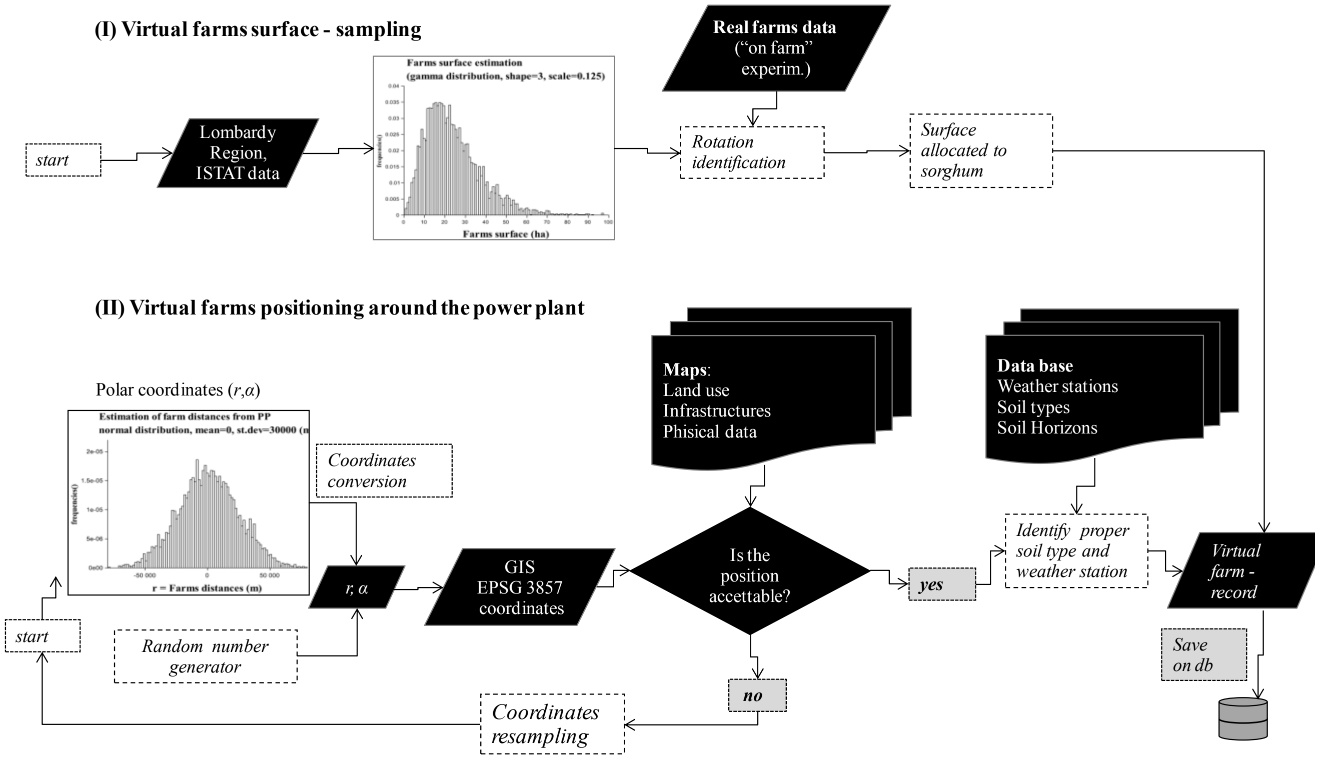


Fig. 3.2 - Schematic representation of the framework used to define the surface (point one) and geographic position (point two and three) of virtual farms population.

Action 3) To simulate the sorghum biomass production in the target cropping area, the CropSyst model, coupled to the "sorghum haying model" (Chapter 2), was run over the mosaic of virtual farm for a 39 years period (1976-2014) under each combination of soil type - weather station that were identified within the N_f suitable farms (Equation 3.2).

The CropSyst model was parameterized using the data calculated for the sorghum hybrid Biomass 133, of medium-late earliness, in a previous experiment (Chapter 2).

Table 3.1 - Description of soils involved in this study. In the table are showed texture composition (sand, silt and clay) for each soils in the first soil horizon Ap. In addition is indicate organic matter, carbon content expressed in % and USDA soil classification.

n°	Soil acronym	Soil horizon	Depth (cm)	Texture (%)			Organic Matter (%)		Bulk density $(g\ cm^3)$	Field capacity $(m^3\ m^{-3})$	Wilting point $(m^3\ m^{-3})$	USDA Classification
				Sand	Silt	Clay	SOC	SOM				
1	CCO1	Ap	40	58.8	30.7	10.5	1.60	2.75	1.55	0.21	0.09	Aquic Haplustepts
2	ISN1	Ap	35	53.1	37.8	9.1	0.50	0.86	1.55	0.22	0.09	Oxyaquic Ustifluvents
3	GOD1	Ap	55	27.2	40.9	31.9	0.90	1.55	1.31	0.33	0.18	Fluventic Haplustepts
4	NOA1	Ap	50	19.8	36.8	43.4	1.23	2.11	1.24	0.41	0.26	Udic Calciusterts
5	RGI1	Ap	40	10.3	61.5	28.2	0.69	1.18	1.30	0.33	0.16	Udic Paleustalfs
6	SGD1	Ap	45	12.8	49.8	37.4	1.42	2.44	1.27	0.37	0.21	Fluvaquentic Endoaquepts
7	VIC1	Ap	55	2.2	64.4	33.4	2.80	4.81	1.26	0.36	0.18	Typic Endoaquepts
8	VRR1	Ap	15	28.1	56.7	15.2	1.20	2.06	1.31	0.33	0.16	Fluvaquentic Haplustepts

In addition the parameterization of CropSyst was modified in order to simulate two additional sorghum genotypes characterized by different growing cycle length. The “early” genotype reached the dough stage (ready for harvesting) 15 days before Biomass 133 and the “late” genotype reached the same stage 15 days later than Biomass 133.

The biomass production simulated by CropSyst was then fed to the “sorghum haying model” (Chapter 2) in order to simulate the sorghum biomass that in each virtual farm can be baled and brought to the power plant (or to the SSF). In the “sorghum haying model” bailing was carried out when biomass humidity was in the range 18% - 30%, as explained in Chapter 2. The total biomass simulated by the CropSyst model, after the simulation with the “sorghum haying model”, was divided into three fractions: “biomass losses”, due to mechanical (7% of total biomass) plus respiration losses (simulated by the “sorghum haymaking model”), “haymaking failure”, biomass that is left unbaled on the field because it had a moisture content > 30% (simulated by the “sorghum haying model”) and “biomass baled” calculated as the difference between “total biomass” and the sum of “biomass losses” and “haymaking failure”.

Action 4) Finally, the “baled biomass” (simulated over the whole target cropping area) was used to compute the probability to exceed 70% (or 64000 Mg DM y^{-1}) of the annual power plant needs during the simulation period (1976-2014).

Probability of exceedance (P_e, %) plots, providing a simple means to describe the probability of exceeding, or falling below, a value of interest (i.e. power plant needs) (Rivington and Wallach, 2015), were used to describe the probability to exceed 70% of biomass plants needs by growing three sorghum genotypes of contracting earliness.

The P_e was calculated following the Weibull's formula (Weibull, 1961) :

$$Pe = m/(n+1) \tag{3.3}$$

This formula requires all values to be sorted from the largest to the smallest. *m* is the rank of the sorted values (*m*=1 for the highest, *m*=n for the lowest) and *n* is the number of values. This enables plotting against a scale of 0 (low probability) to 1 (high probability). The Weibull’s plotting position can be used to estimate both central tendency and range of data, expressed as exceedance probabilities Grissino-Mayer 1995.

3.2.3 Energy balance

In order to compare the energy required (input) and that produced (output) by sorghum cultivation a simplified energy balance, from cradle to farm gate (Djomo *et al.*, 2011), was carried out considering net primary energy (NPE) or primary energy requirement (PER) (Zhai *et al.*, 2013). These are fundamental metrics which include all the energy used from extraction of natural resources, preparation of upstream materials, and each step of manufacturing the delivered device without considering any renewable resource (i.e. sun, biomass etc). In the case of fossil fuels NPE considered also the energy content in the fuel expressed as low heating value (LHV)

The total energy costs (E_t) were divided into indirect energy costs (E_i) and direct energy cost (E_d) according to Hülsbergen *et al.*, 2001. In addition the fixed and variable energy quote involved in biomass sorghum production was quantified.

The technical characteristics of the agricultural machinery involved in all field operations, from soil preparation to field sorghum bales stacking, were recorded during field trials. When necessary the missed characteristics were implemented by data derived from agricultural machinery manufacturers.

Energy input was converted from physical quantities to energy units using the software GaBi 6.3 software (Thinkstep Professional, 2015) measured through coefficients of energy transformation according to the commercial database (Ecoinvent 2.2, 2010) (Table 3.2).

The input for each field operation, from sowing to field sorghum bales stacking, were calculated separately for agricultural machinery (tractors and equipment), fossil fuels, lubricants and farm inputs (seeds, herbicides, fertilisers, shed, etc.). Energy costs for delivering primary materials (diesel, seeds, fertilizers, etc.) inside of the farm, was calculated.

The energy input for the fabrication of agricultural machinery (tractors and equipment) was calculated taking into account their weight, the time of use for each field operations and a lifespan of 10 years based on 1 hectare. Two differently powered tractors were used, one for ploughing, harrowing and harvest (mower-conditioner and baler) (162 kWh) and one for the other field operations (110 kWh). The fossil fuel cost of various field operations was divided in diesel used for field operations, for harvesting operations and for field sorghum bales stacking operations taking into consideration the NPE of diesel of 49.3 MJ kg^{-1} in accordance to the commercial database (Ecoinvent 2.2, 2010). This value includes a LHV of diesel fuel combustion of 43.1 MJ kg^{-1} according to Edwards *et al.*, (2011).

The diesel used for operations was estimated by the determination of fuel consumption according to Fröba and Funk, 2004. To increase the reliability of the study, the diesel used during harvesting and bales stacking operations was proportional to the biomass present on the field.

The energy cost for fertilizer manufacturing was estimate starting from the quantity used in the field: 80 and 60 kg $ha^{-1}y^{-1}$ respectively for N, as urea and P_2O_5 as superphosphate. Energy input for farm buildings (40 years, lifespan) was calculated taking into consideration the amount of shed space to be attributed to a work process according to Nemecek *et al.*, 2007.

Table 3.2 - Physical quantities and energy coefficients for selected agricultural input regarded the three sorghum genotypes. Energy coefficients was in according to Ecoinvent 2.2, 2010.

Energy input		**Sorghum genotype**			**Energy coefficient**	**Unit of misure**
		Early	**Medium-late**	**Late**		
		Quantity (Kg $ha^{-1}y^{-1}$)				
Diesel consumption *		141.76	143.64	148.65	49.3	MJ kg^{-1}
Agricultural machinery						
	Tractors	2.93	2.93	2.93	120	MJ kg^{-1}
	Equipment	3.73	3.73	3.73	75.2	MJ kg^{-1}
Lubricatings oil		0.41	0.41	0.41	74.8	MJ kg^{-1}
Machinery shed		0.01	0.01	0.01	47.5	MJ $(m^2)^{-1}$
Seeds		10	10	10	16.6	MJ kg^{-1}
Fertilizers						
	N	80	80	80	60.2	MJ kg^{-1}
	P_2O_5	60	60	60	30.6	MJ kg^{-1}
Plastic						
	Twine	1.7	1.5	1.56	69.9	MJ kg^{-1}
Herbicides**						
	Terbutilazine	0.56	0.56	0.56	169	MJ kg^{-1}(a.s.)
	S-Metolachlor	0.94	0.94	0.94	184	MJ kg^{-1}(a.s.)

* Total diesel consumption for all operations
** Expressed in terms of active substance (a.s.)

The total amount of engine and hydraulic oil needs during the lifetime of the agricultural machinery was calculated according to Ammann and Stadler, 1998. The energy quota attributed to the herbicides was obtained by multiplying the amount of active substance (a.s.) used by the relative energy coefficients for S-Metolachlor and Terbutilazine. Energy input for seeds production was calculated starting from the quantity used (10 kg ha^{-1}). In addition the energy cost related to the amount of plastic material (twine) used for baling was also calculated proportion to the biomass baled.

The energy output was defined as the calorific value of the harvested biomass, that was computed by multiplying the amount of biomass produced (Mg DM ha^{-1}) for the low heating value on dry bases (LHV_{dry}). LHV_{dry} (15.7 MJ kg^{-1}) was calculated starting from $LHV_{14\%}$ (13.18 MJ kg^{-1}) according to the technical power plant project (Original approved technical details of sorghum power plant, 2012). All simulated years were considered in the calculation of the energy balance, including the years in which sorghum production was equal to 0 due to haymaking failure. The efficiency of biomass sorghum production, for each genotype, was evaluated as Energy Return on Investment (EROI) and also as Net Energy Gain (NEG). In addition the Energy Use Efficiency (EUE), defined as the energy required to produce a unit of dry matter, was estimate from each sorghum genotype (Table 3.3).

Table 3.3 - Definition of energy parameters and indexes (in terms of non-renewable primary energy).

Parameter	Definition	Unit of misure
Direct energy input (E_d)	Diesel consumption	MJ ha^{-1} y^{-1}
Indirect energy input (E_i)	Agricultural machinery, seeds, fertilizers, herbicides, shed, etc.	MJ ha^{-1} y^{-1}
Total energy input (E_t)	$E_t = E_d + E_i$	MJ ha^{-1} y^{-1}
Energy output (EO)	Energy contained in the biomass	MJ ha^{-1} y^{-1}
EROI	EO/E_t	/
Net Energy Gain (NEG)	EO - E_t	MJ ha^{-1} y^{-1}
Energy Use Efficincy (EUE)	NEG/biomass baled (Mg DM ha^{-1})	MJ Mg^{-1} y^{-1}

3.2.4 Statistical analysis

Statistical analysis was by analysis of variance (ANOVA). The model used was one-way ANOVA using IBM – SPSS 21 (IBM Corporation, Armonk, New York, USA), given the normality of distributions (Shapiro and Wilks test; Shapiro and Wilk, 1965) and the homogeneity of variances (Levene's mean-based test; Levene, 1960). The separation of means was obtained by post-hoc Tukey's HSD test. A regression analysis to study the relation between haymaking failure and rainfall during field drying process was carried.

3.3 Results

Biomass production of the sorghum genotype of medium-late earliness (Biomass 133) measured during the experimental trials carried out on 20 farms in 2010 is presented in Table 2.2b (Chapter 2). Biomass production ranged from 11.1 to 26.9 Mg DM ha^{-1} and was on average 19.9 Mg DM ha^{-1}. The lowest yield was obtained when sorghum was planted immediately after the harvest of winter wheat. Biomass production refers to the total aboveground biomass available at harvest, without considering mechanical and respiration losses. The average loss of biomass, due to the sum of mechanical losses (7%) and respiration losses (16.6%, as simulated by the "sorghum haying model"), was on average 23.6%. Therefore, ignoring haymaking failures (that did not occur in 2010) the net biomass yield, baled and available for combustion at the power plant was 15.2 Mg DM ha^{-1}. In these specific conditions and considering the above calculated net biomass yield (15.2 Mg DM ha^{-1}) the area to be cultivated with sorghum to satisfy 70% of biomass plant needs (64000

Mg DM y^{-1}), is therefore 4221.6 hectares. This acreage was taken as a reference for the creation of the mosaic of virtual farms following the procedure described in Action 2c of the material and methods and using Equation 3.2. The mosaic of virtual farms was composed of 486 (***N_f***) farms having an average acreage of 8.46 ha.

3.3.1 Long term simulation of biomass sorghum production

To simulate the production of baled sorghum biomass in the target area, the CropSyst model, coupled to the "sorghum haying model" (Chapter 2), was run over the mosaic of virtual farms for a 39 years period (1976-2014).

In the long term simulation, the average amount of rainfall during the sorghum cropping season was 271, 320 and 365 mm respectively for the early, medium and late genotypes (Fig. 3.3).

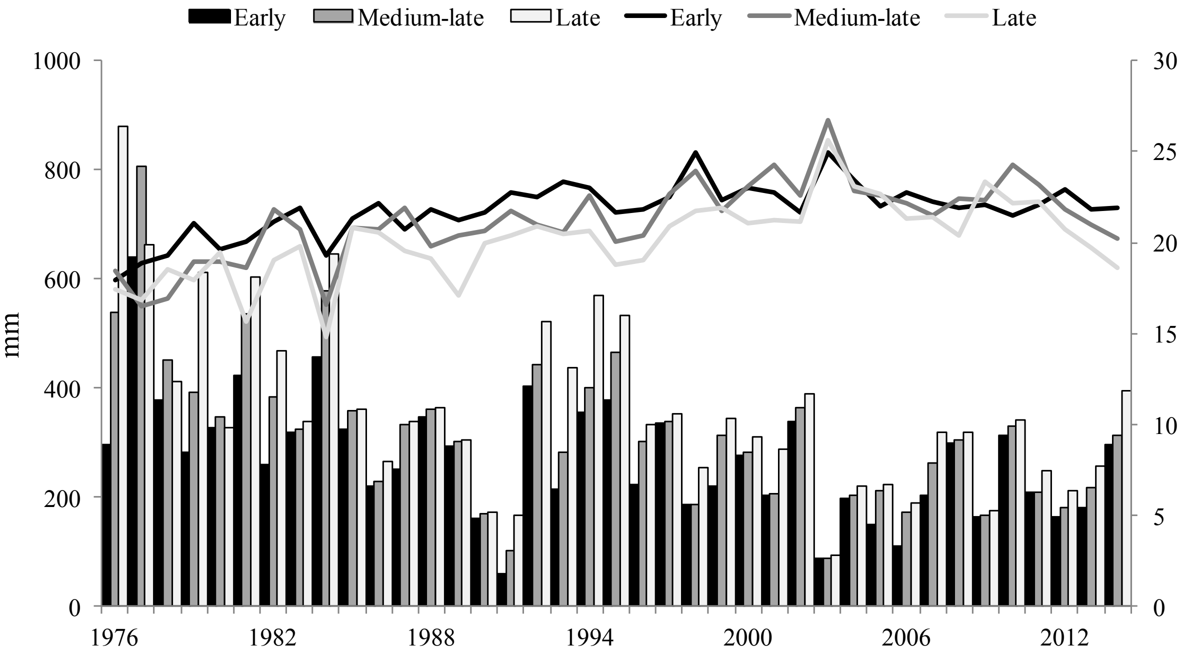


Fig. 3.3 - Rainfall and average temperature trends in the simulated period (from 1976 to 2014). Columns are rainfall (left Y-axis) average yearly; Lines are yearly average temperatures (right Y-axis). The quantity of rainfall and average temperature respectively increase and decrease from early to late genotype.

Sorghum cropping season was divided into two periods, from sowing to harvesting and from harvesting to baling. The total amount of rainfall until harvesting was on average 250, 285 and 319 mm respectively for early, medium and late genotype. From harvesting until baling, there were 21, 35 and 46 mm of rain for the early, medium-late and late genotype respectively.

The average temperature in the growing season and particularly in the period from harvesting to baling decreased from the early to the late sorghum genotype. An average temperature decrease of

3.4°C was measured in the interval between the harvest of the earliest genotype (14/08) and the harvest of the latest genotype (13/09).

Total biomass simulated by CropSyst, on the average of 39 years, significantly increased (ANOVA *F:* 4.609; *P:* 0.012) from the early to the late genotype (Fig. 3.4).

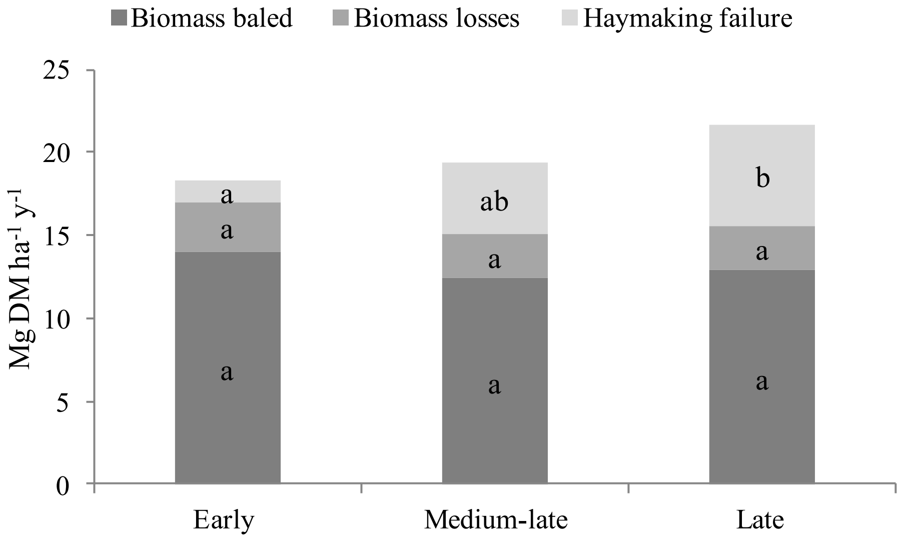


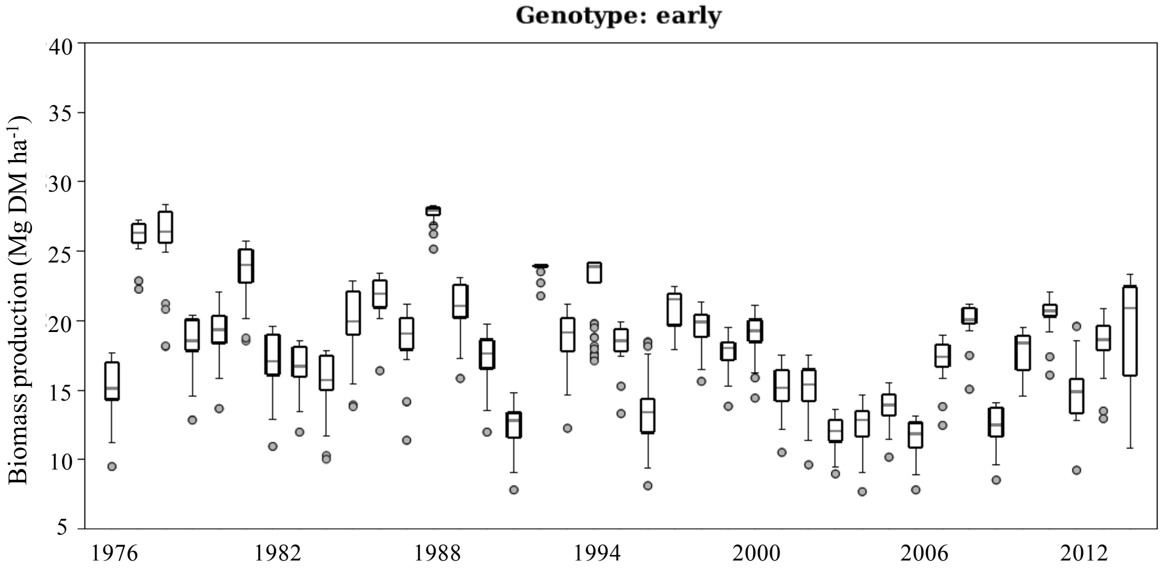
Fig. 3.4 - Simulation results related "biomass baled", "biomass losses" (due to mechanical and respiration losses) and "haymaking failure". Different letters inside each columns indicate different means for $P < 0.05$ (Tukey's HSD test).

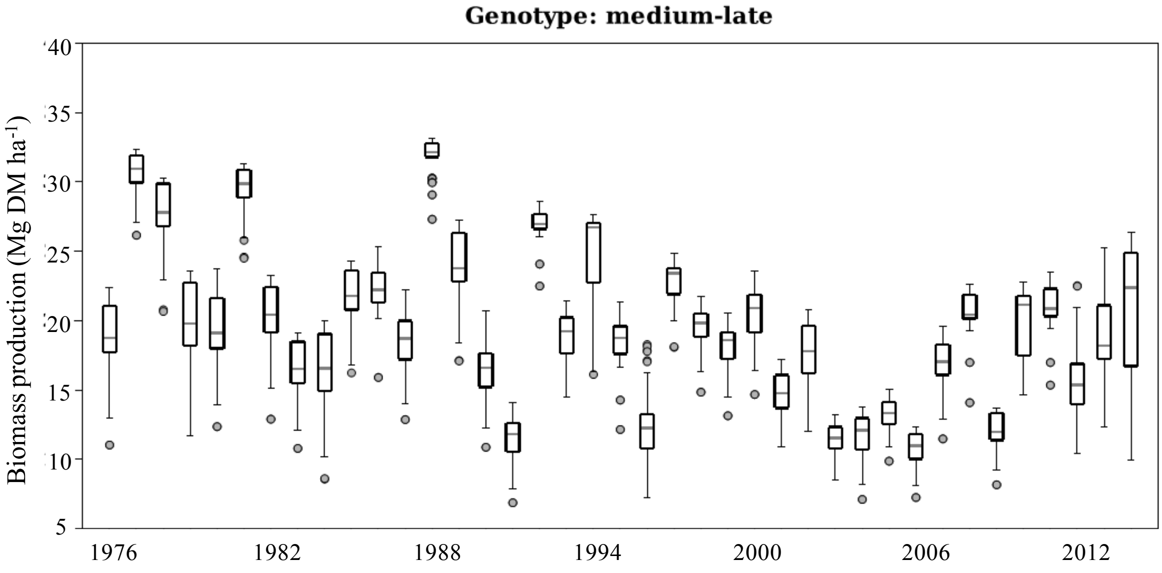
Biomass baled simulated by the "sorghum haying model", was not statistically different between genotypes (ANOVA *F*: 0.76 *P*: 0.47) with the earliest genotype tending to have higher biomass baled than the medium and late ones (Fig. 3.4).This is mainly a consequence of haymaking failure that increased statistically (ANOVA *F*: 3.62 *P*: 0.03) from the early to the late genotype (Fig. 3.4). Biomass losses (mechanical and respiration) were on average 14.2% of total biomass production and statistical differences were not found among the three genotypes (ANOVA *F*: 0.63 *P*: 0.54).

To predict a relationship between haymaking failure (Mg DM losses ha^{-1}) and rainfall (mm) during field drying, a regression analysis was performed. Haymaking failure (Mg ha^{-1} y^{-1}) is linearly correlated with rainfall during field drying (R^2= 0.56, P< 0.0001). The regression coefficient obtained was 0.14 Mg DM losses ha^{-1} mm^{-1}.

Yearly simulations of total biomass (Mg DM ha^{-1}) for the three genotypes, is presented in Fig. 3.5. Biomass production of the early genotype ranged from a minimum of 11.6 Mg DM ha^{-1} to a maximum of 27.6 Mg DM ha^{-1};the medium genotype ranged from 10.8 to 31.7 Mg DM ha^{-1}; the late genotype ranged from 11.7 to 34 Mg DM ha^{-1} Minimum biomass production was obtained in 2006 due to the lower rainfall (157 mm) in the growing season while the minimum production was obtained in 1988 due to the higher rainfall (354 mm) in the growing season, respectively for all three genotypes.

Considering the whole area dedicated to sorghum cultivation (4221.6 ha), at harvest the total simulated biomass was on average 77154 Mg DM y^{-1}, 81623 Mg DM y^{-1} and 91383 Mg DM y^{-1}, respectively for the early, medium and late genotype. The sorghum biomass potentially available to the power plant is however a fraction of that produced on field and losses encountered during the haymaking process should be taken into account.





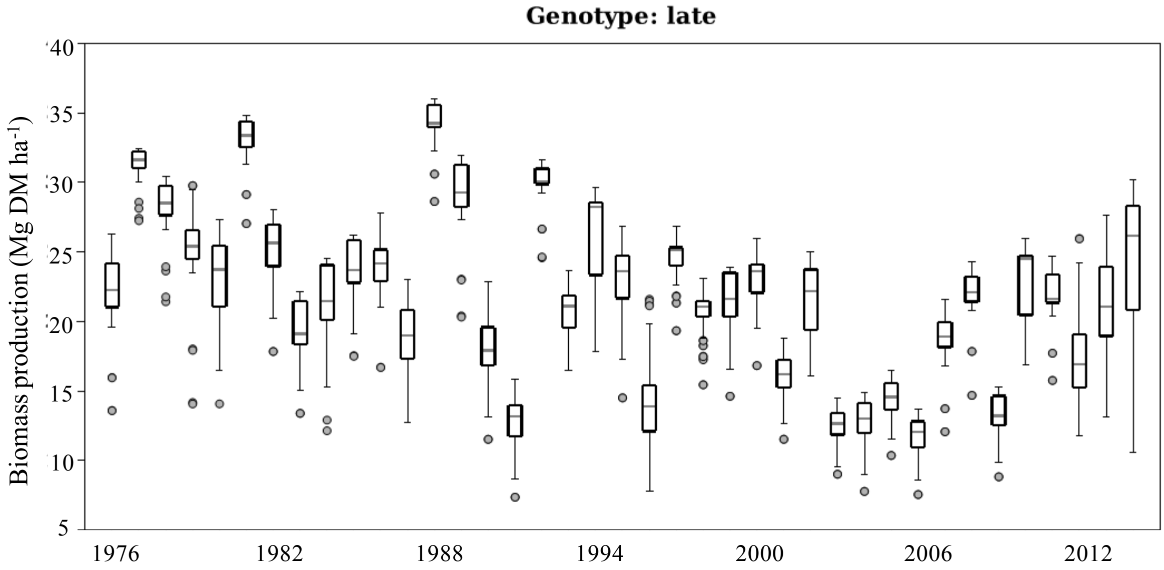


Fig. 3. 5 - Variability of total biomass production of the three sorghum genotypes considered in this study. In detail, each box plot describes biomass production range relative to all 486 virtual fields simulated and its variability. Box plots reveal big differences among simulated years in terms of mean, median, lower and upper limits.

Simulation of baled biomass, potentially available for combustion at the power plant, calculated with the “sorghum haying model” (Chapter 2) is presented in Fig. 3.6.

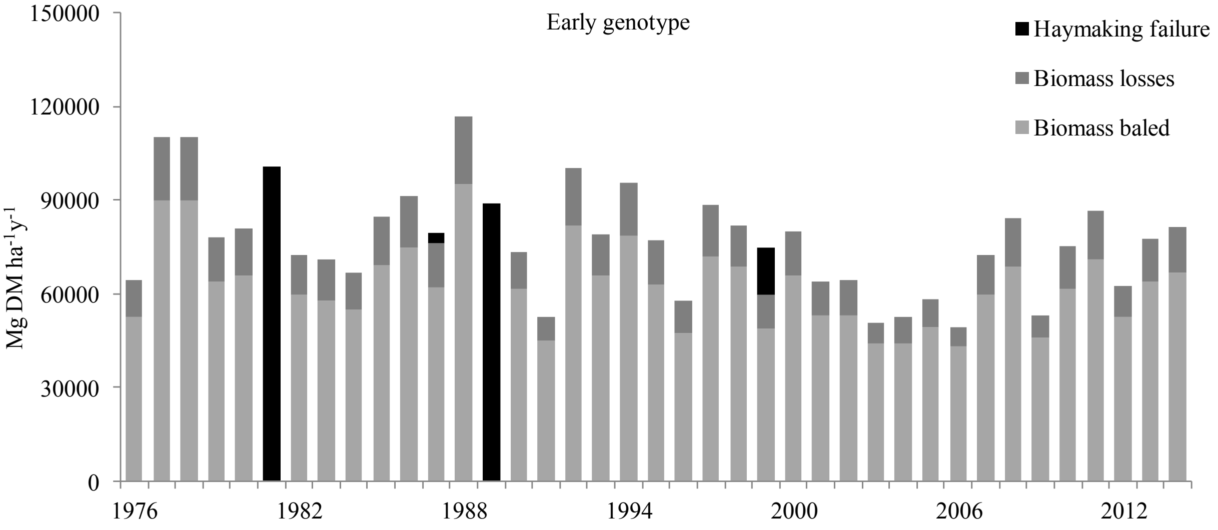
The baled biomass for the early genotype was on average 59270 Mg DM y^{-1} (14.04 Mg DM ha^{-1}), due to an average biomass loss (mechanical plus respiration) during field drying process of 16.27% (12551 Mg DM y^{-1}) and to haymaking failures that further decreased baled biomass by 6.91% (5333.5 Mg DM y^{-1}). In particular the model simulated total haymaking failure in two years, that resulted in a loss of 6.3% (4868.4 Mg DM y^{-1}), and two partial haymaking failure (i.e haymaking failure only occurred in some of the farms), that resulted in a loss of 0.61% (465 Mg DM y^{-1}) of the total biomass. The baled biomass ranged from 43197 Mg DM y^{-1} in the worst year to 95120 Mg DM y^{-1} in the best year.

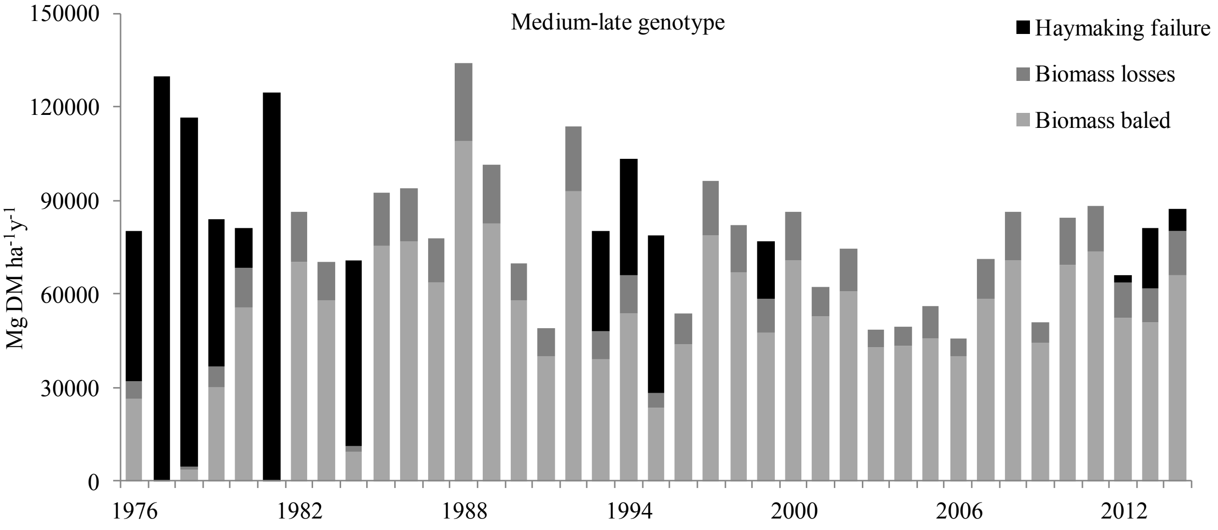
The baled biomass for the medium-late genotype was on average 52459 DM Mg y^{-1} (12.43 Mg DM ha^{-1}), due to an average biomass loss (mechanical plus respiration) during field drying of 13.73% (11210 Mg DM y^{-1}) and due to haymaking failure that further decreased biomass by 22% (17954 Mg DM y^{-1}). In particular the model simulated total haymaking failure in two years, that resulted in a loss of 8% (6521.9 Mg DM y^{-1}), and twelve partial haymaking failure, that resulted in a loss of 14% (11431.9 Mg DM y^{-1}) of the total biomass. The baled biomass ranged from 3802 Mg DM y^{-1} (0.9 Mg ha^{-1}), in the worst year, to 109128 Mg DM y^{-1} (25.8 Mg DM ha^{-1}), in the best year.

The baled biomass for the late genotype was on average 54447 DM Mg y^{-1} (12.89 Mg DM ha^{-1}), due to an average biomass loss (mechanical plus respiration) during field drying of 12.7% (11394

Mg DM y^{-1}) and due to haymaking failure that further decreased baled biomass by 27.9% (25541 Mg DM y^{-1}). In particular the model simulated total haymaking failure in four years, that resulted in a loss of 12.7% (11658.4 Mg DM y^{-1}), and thirteen partial haymaking failure, that resulted in a loss of 15.2% (13882.5 Mg DM y^{-1}) of the total biomass. The biomass baled ranged from 2952 Mg DM y^{-1} (0.7 Mg ha^{-1}) in the worst year to 113773 Mg DM y^{-1} (26.9 Mg DM ha^{-1}) in the best years.

The highest incidence of haymaking failures occurred with the late sorghum genotype, that was affected by a total haymaking loss (on all the farms) in 4 out of 39 years of simulation, while 13 of 39 years were characterised by partial haymaking failures (Fig. 3.6).





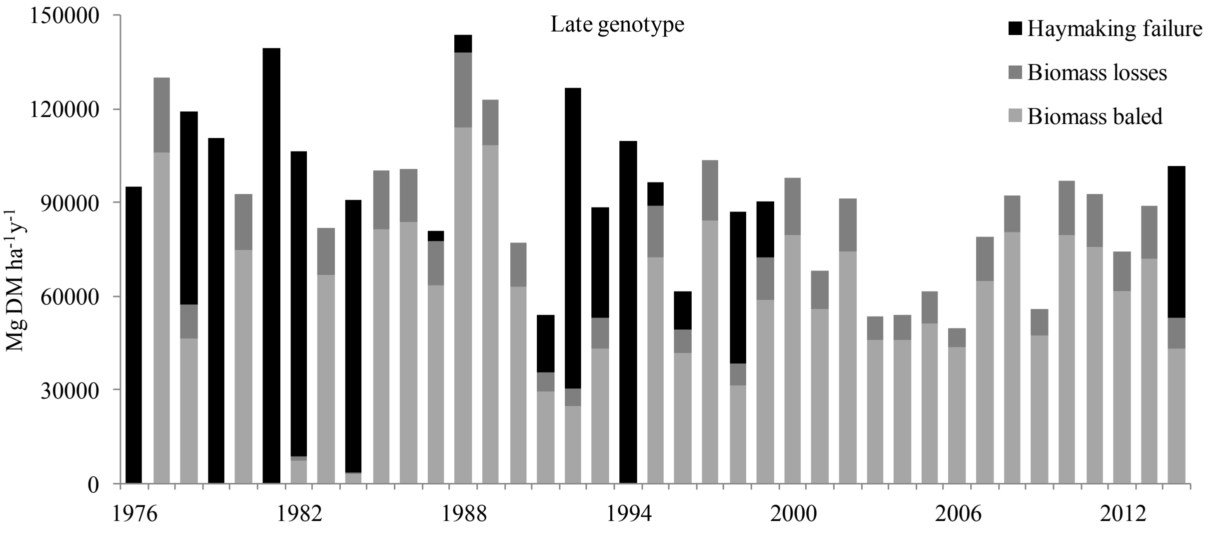


Fig. 3.6 - Total biomass production of the three sorghum genotype divided in “Biomass bale”, “Biomass losses” due to mechanical and respiration losses and “Haymaking failure”.

3.3.2 Quantification of the probability to exceed a definite biomass need

The probability of the three sorghum genotypes to exceed a given biomass production in the simulated period (39 years) is presented in Fig. 3.7.

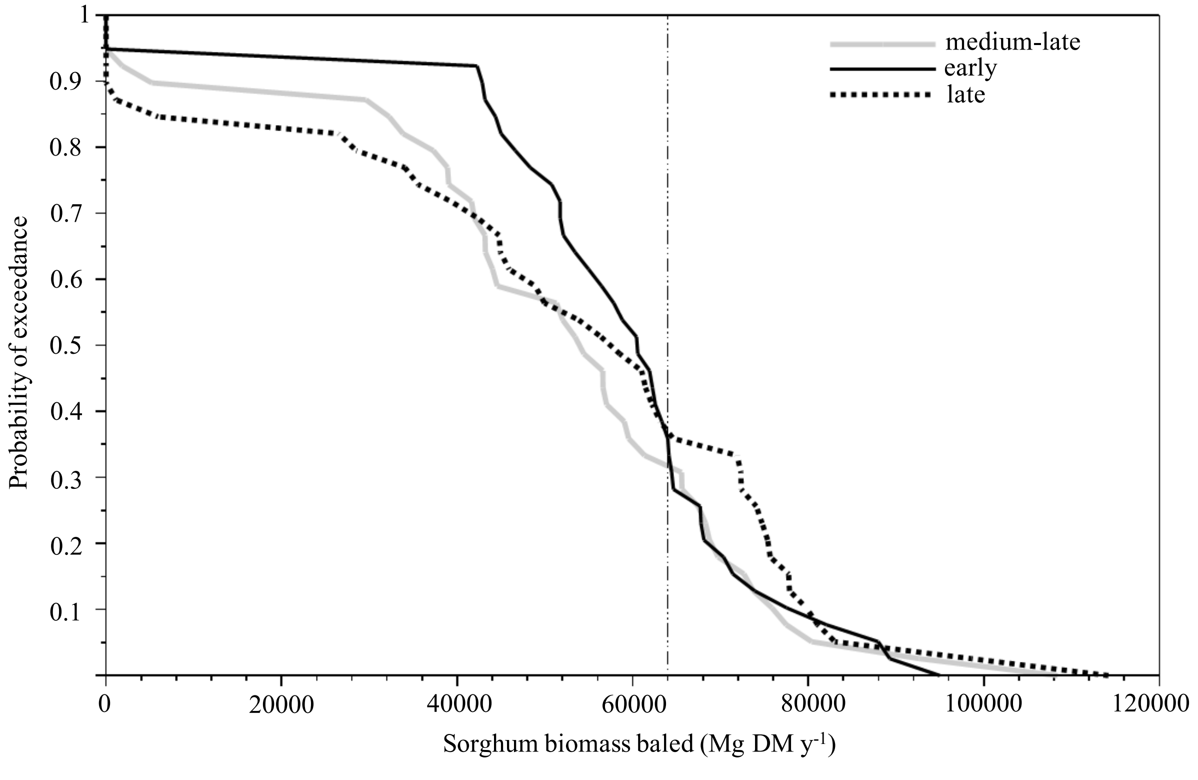


Fig. 3.7 - Probability (on the Y-axis) to exceed a certain biomass production (Mg DM y^{-1}) which is indicated on the X-axis. The line represent the probabilities to cover power plant needs as comparison between the three genotypes characterized by different earliness.

Genotype earliness affected the probability to exceed ($P_{e,}$ %) a determined biomass production threshold: the early genotype showed the highest P_e until approximately the threshold of 62000 Mg DM y^{-1}, at higher threshold levels and until 80000 Mg DM y^{-1} the latest genotype showed the highest P_e, while above P_e dropped under 0.1 above 80000 Mg DM y^{-1}. Referring to the target threshold of 64000 Mg DM y^{-1},(or 70% of biomass plant needs) this was exceeded by the early genotype in 15 of the 39 simulated years (P_e= 0.38), by the late genotype in 14 years (P_e= 0.36) and by the medium-late genotype in 12 years (P_e= 0.31).

3.3.3 Energy balance and energy efficiency

The highest contribution to total energy costs (E_t) came from the fixed energy quote (on average 85% of E_t), composed by diesel used during field operations, lubricating oil, fertilizers, and other farm inputs (Table 3.4). In particular the main fixed energy input were diesel used during field operations and nitrogen fertilizers that were responsible for 39.4% and 37.4% of fixed energy quote, respectively.

Variable energy quote, composed by diesel used during harvesting and field sorghum bales stacking operations and by plastic twine for baling, was responsible on average for 15% of the total energy costs (E_t). Variable energy quote increased from the early to the late genotype due to the higher diesel consumption for harvesting operation that is proportional to biomass production.

Diesel used during field sorghum bales stacking and plastic twine consumption was not statistically significant between genotypes for their similar baled biomass level.

Energy flows resulted from energy balance are presented in Fig. 3.8. On average, total energy input (E_t) required to produce biomass sorghum was 15 GJ ha^{-1} y^{-1}, total energy output (E_O) was 206 GJ $ha^{-1}y^{-1}$ and net energy gain (NEG) was 191 GJ ha^{-1} y^{-1}.

Indirect energy inputs (E_i) were the same for the three sorghum genotypes, while direct energy input (E_d) increased from the early to the late genotype, due to diesel consumption for harvesting that is proportional to biomass yield. As a consequence total energy input (E_t) increased from the early to the late genotype (14.9, 15.2 GJ ha^{-1} y^{-1}) (Table 3.4).

The highest energy output (E_O) (220.5 GJ ha^{-1} y^{-1}) was obtained with the early genotype followed by the late and early genotype. This trend is related to biomass baled that increased from the early to the late genotype.

The energy performance of the three sorghum genotypes was explored by analysing the EROI, NEG and EUE. For the early genotype EROI and EUE were 0 and NEG was negative due to total haymaking failures in two years (1981 and 1989); the medium-late genotype had EROI and EUE equal to 0 in 1977 and 1981 while NEG was negative in three years (1977, 1981 and 1988); EROI and EUE for the late genotype were 0 in four years (1976, 1979, 1981 and 1994) while NEG had a negative value in five years (1976, 1979, 1981, 1984 and 1994).

Table 3.4 - Energy characterization of the three sorghum genotypes: total energy input, output and energy-base indices.

Energy input		**Sorghum genotype**	
	Early	**Medium-late**	**Late**
		(GJ ha^{-1} y^{-1})	
Diesel consumption			
field operations	5.08	5.08	5.08
harvesting operations	1.34	1.47	1.72
field stacking operations	0.57	0.54	0.53
Direct energy input (E_d)	**6.99**	**7.08**	**7.33**
Agricultural machinery			
Tractors	0.35	0.35	0.35
Equipment	0.28	0.28	0.28
Lubricatings oil	0.03	0.03	0.03
Machinery shed	0.04	0.04	0.04
Seeds	0.17	0.17	0.17
Fertilizers			
N	4.80	4.80	4.80
P_2O_5	1.82	1.82	1.82
Herbicides	0.27	0.27	0.27
Plastic (twine for baling)	0.12	0.10	0.11
Indirect energy input (E_i)	**7.88**	**7.87**	**7.87**
Total energy input (E_t)	**14.87**	**14.95**	**15.20**
Energy output			
Biomass baled (Mg DM ha^{-1} y^{-1})	14.04	12.43	12.90
Total energy output (E_O) (GJ ha^{-1} y^{-1})	220.45	195.12	202.52
NEG (GJ ha^{-1} y^{-1})	**205.58**	**180.17**	**187.32**
EUE (GJ Mg^{-1} DM y^{-1})	**1.06**	**1.20**	**1.18**
EROI	**14.83**	**13.05**	**13.32**

For all sorghum genotypes the energy output was at least tenfold higher than the non-renewable energy input and the EROI was on average 13.7 while on average NEG was 191 GJ ha^{-1} y^{-1}.

The highest EROI and NEG were achieved by the early genotype followed by late and medium-late genotypes. The highest energy use efficiency (EUE) was achieve by the medium-late sorghum genotype followed by the late and the early ones (Table 3.4).

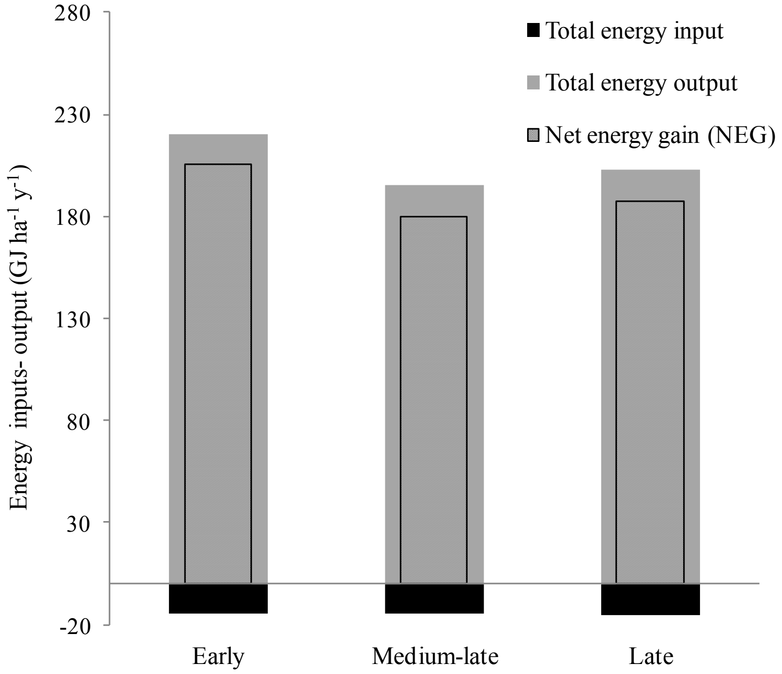


Fig. 3.8 - Energy input-output and Net energy gain (NEG) of the three sorghum genotype subjected to energy analysis.

3.4 Discussions

Risk is an intrinsic component in the decision making of all business activities (Thorne and Hennessy, 2005) and particularly in agriculture, that is exposed to the high variability of some production factors, such as weather conditions (Clancy *et al.*, 2012). Using the sorghum haying model, developed in Chapter 2, coupled to the simulation model CropSyst, a long term simulation (39 years) was run on the potential supply area of a power plant to calculate the probability to satisfy a determined biomass requirement using genotypes of contrasting earliness.

To mimic the annual yield variability across the biomass supply area a mosaic of virtual farms was created in the catchment area of the power plant and on them the simulation was carried out. This also enabled the collection of logistic data, relative to the spatial distribution of the biomass that could be used to complete the energy balance of the biomass production system including cost for transport.

The simulation confirmed the findings of Chapter 2, that biomass baled, biomass losses and haymaking failure are significantly affected by genotype earliness, with the early genotype achieving the highest biomass baled thanks to the lowest haymaking failure, despite it having the lowest biomass yield at harvest (Fig. 3.4). Haymaking failures are therefore a major constraint of biomass production from sorghum, with rainfall playing a major role in determining the success of biomass baling.

As expected, the long-term simulation showed a positive relationship between haymaking failure and rainfall during the field drying process. Late genotypes, being harvest when rain is more probable, have and higher risk to fail field drying, as reported by Quaranta *et al*., (2010).

On the other hand, biomass loss due to respiration, that is enhanced at higher temperatures, is slightly higher with the early genotype that is harvested in warmer weather. Overall, the highest average biomass baled (14.04 Mg DM ha^{-1}), combined with other agronomic advantages (i.e. an early genotype frees the field sooner than later ones, leaving more time for the subsequent crop) makes the earliest genotype the most favourable choice for biomass production, and it provides the highest probability of reaching the target production of 64000 Mg DM y^{-1} on the target area (Fig. 3.7).

The combination of models tested in this work represents a valuable management tool that can be used to identify the genotype that, on a specific area, can provide a given production target with the lowest risk. The same tool can be also used to predict, for a given sorghum genotype, the risk related to supplying its biomass to an energy plant, and the amount of land needing to be cultivated can be calculated at a consequence of that risk prediction. For example, considering the results of this study, a probability of 50 % to exceed 64000 Mg DM y^{-1} (or 70% of power plant needs) is achieved by cultivating 4557.9, 5159.6 and 4961.6 ha using the early, medium-late and late genotype respectively. These target areas could be used as basis for long-term biomass supply contracts between the industry (power plant) and the farmers associations to guarantee the biomass supply necessary to cover power plant needs.

Considering the importance of achieving a favourable energy balance in bioenergy production (Arodudu *et al*., 2013), the yield data obtained from the simulation study were used to carry out a cradle to farm gate energy balance, in particular discriminating the effect of the three genotypes.

All genotypes had a positive energy balance for the energy input spent in sorghum cultivation was lower than the energy embedded in the biomass produced. The early genotype showed the highest energy performance, as expressed by the energy indexes EROI and NEG, and the lowest EUE, for its highest production of biomass baled coupled to energy costs for cultivation very similar to those considered for the other genotypes.

Data on biomass sorghum energy balance in literature are very limited and direct comparison is impaired due to differences in calculation systems. Monti and Venturi (2003), considering biomass yield of fibre (genotype H128) and sweet (genotype Keller) sorghum, without accounting for haymaking losses, found respectively 18.8 Mg DM ha^{-1} and 21.2 Mg DM ha^{-1}, which is similar to the value found in this study for similar yield production. The contribution of this study to advance the knowledge needed to evaluate and implement biomass production from sorghum at regional level lays in the possibility to calculate biomass loss during field drying and losses due to haymaking failure. This enables the calculation of realistic energy balance that take into account situations in which biomass production is totally lost due to haymaking failure. In our simulations if the years in which biomass is totally lost are not considered the EROI and NEG increase on average by 6 and 7.2% respectively and EUE decrease on average by 10%, on the average of all genotypes. Considering that a bioenergy system should have a EROI > 3 to be sustainable and support socio-economical functions (Hall *et al.*, 2009), the baled biomass simulated in this study and converted to electricity considering a net overall electrical efficiency (η_e) of 20.5 % (Original approved technical details of sorghum power plant, 2012).can be used to explore the overall sustainability of electricity production in the target environment. The early genotype had a EROI value of 3.04 on average and it was higher than 3 in 56% of the simulated years. In 5.13% of the simulated years EROI was less than 1, which indicates that the energy input was higher than the electricity produced. The medium-late and late genotypes showed lower energetic performance than the early one, EROI was lower than 3 in 54% and 51.3% of the cases for the medium-late and late genotype respectively. EROI was lower than 1 in 10.3% of the years for medium-late and 15.4% for the late one.

3.5 Conclusions

In this study was investigated the production risk of three sorghum genotypes of contrasting earliness to exceed the 70% (or 64000 Mg DM y^{-1}) of biomass power plant needs in the Po Valley.

CropSyst model, coupled by "sorghum haying model", was used to simulated in a long-term simulation the total biomass production, biomass losses (mechanical and respiration losses) and haymaking failure (partial and total) quantifying the biomass baled available to power plant.

In a long-term simulation, the early genotype showed the highest biomass baled due to the lower incidence of haymaking failure (6.9%). In addition the early genotype showed the highest probability (or the lower production risk) to exceed the threshold of 64000 Mg DM y^{-1} based on a target cropping area of 4221.6 ha. The early genotype also showed the highest EROI (14.8), NEG (205.6 GJ ha^{-1} y^{-1}) and the lower EUE (1.06 GJ Mg^{-1} DM y^{-1}) due to its highest biomass baled.

To achieve the 0.5 probability to exceed the target biomass baled production the number of hectares to be cultivated with the early, medium-late and late genotypes should be 4557.9, 5159.6 and 4961.6 ha, respectively.

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CHAPTER 4

Environmental impact assessment of a biomass sorghum fuelled power plant in the Po Valley

The chapter is submitted as:

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Environmental impact assessment of a biomass sorghum fuelled power plant in the Po Valley

Abstract

A Life Cycle Assessment (LCA) was carried out to explore the environmental impact and energy performance of three biomass sorghum genotype characterized by different earliness (early, medium-late and late) used to generate electricity by direct combustion in a biomass power plant in the Po Valley. To fully cover the needs of the power plant sorghum was complemented by winter wheat straw. To increase the reliability of the study, soil organic carbon change (ΔSOC) relative to the straw removal was estimated in a long-term simulations of 39 years. Indirect land use change (iLUC) emissions were also considered in this study. To test the effect of the many assumptions defined in the LCA model set-up, we performed a sensitivity analysis over several parameters to explore the changes in environmental impacts. Late sorghum genotype shows the lowest average GHG emissions (76.58 g $CO_{2eq.}MJ^{-1}{}_{el.}$) while medium-late and early genotype show emissions value of 80.52 g $CO_{2eq.}$ $MJ^{-1}{}_{el.}$ and 80.43 g $CO_{2eq.}MJ^{-1}{}_{el.}$ respectively. All values are lower than reference fossil systems considered.

The decomposition of the overall GHG emissions shows a linearity factor linked to the amount of sorghum production but the emissions associated to sorghum production have a non-linearity factor due to the mechanical and respiration losses, and associated SOC accumulation, which are instead driven by the climate in the specific year considered.

The application of $DeNO_x$ selective no catalytic reaction (SNCR) may cause a trade-off between an increase in the climate change impact due to additional N_2O emissions, while mitigating all other impacts, especially acidification potential and photochemical oxidant formation. The inclusion of carbon emissions due to iLUC contributes to about 10% of total GHG emissions. The climate change impact category results to have a small sensitivity to the changes in emissions/accumulation of SOC due to straw removal and sorghum incorporation.

The highest EROEI was reached by early genotype (2.59) followed by late (2.56) and medium-late (2.49).

Keywords: Biomass sorghum, GHG emissions, environmental impact, Life Cycle Assessment, EROEI, $DeNO_x$ SNCR system, iLUC

4.1 Introduction

In a context characterized by the strong dependency on the use of fossil fuels, climate change, food security and energy provision are the major driving forces to be addressed in order to find and/or implement a sustainable way to produce energy.

Since 2009 the European Union (EU) has been promoting bioenergy as one of the main renewable, low-carbon sources to achieve its ambitious climate and energy targets for 2020 and beyond (Directive 2009/28/EC). More recently, a new EU energy strategy (COM/80, 2015) has called for a profound transformation of Europe's energy system, based on a more secure, sustainable and low-carbon economy, with a commitment to achieve by 2030 at least 27% share of renewable on the EU's energy consumption and 40% greenhouse gas emission reduction relative to emissions in 1990 (COM/015, 2014).Bioenergy is currently the major source of renewable energy in the EU and the demand for biomass in the EU and world-wide is increasing, both in the heating and in the power sector.

In Italy the interest to use biomass to produce bioenergy increased following the 2006 European Reform of sugar Common Market Organisation (320/2006/EC) were released an uncultivated large agricultural surface previously cultivated with sugar beet (*Beta vulgaris* L.).

In particular, the Regulation 318/2006/EC, authorized a drastic reduction of the sugar production, thanks to specific EU funds for divesting the establishments, decommissioning and cleaning of the industrial areas. Other EU funds were addressed to convert the sugar activity, provided that it reactivated the agro-industrial sector in order to compensate the affected agricultural sector. For this reason the Italian government, in March 2006, decided to issue the Law 81/2006 with the aim to promoted the conversion of disused sugar factories in to other agro-industrial activities giving the possibility to use alternative cultures instead of sugar beet.

In this study sorghum (*Sorghum bicolor* (L.) Moench) represents the main suitable feedstock to electricity generation by direct combustion in a biomass power plant in accordance to the conversion plan of a sugar factory in the Po Valley (northern of Italy). This industrial conversion at the same time had to be profitable for farmers and be able to exploit the large surface previously cultivated with sugar beet.

Among annual bioenergy crops, biomass sorghum is considered a crop that could play an important role in energy production as a dedicated lignocellulosic energy crop (Rooney *et al*., 2007), particularly for anaerobic digestion and second generation bioethanol production (Amaducci *et al*., 2000, Davila-Gomez *et al*., 2011, Agostini *et al*., 2015) as well as for power generation by direct combustion (Bennett and Anex, 2009, Zagada-Lizarazu and Monti, 2012).

Sorghum is an annual C4 herbaceous crop of tropical origins with the capacity to adapt to different environmental conditions and has attracted attention over the years as an alternative to conventional crops.

The efficient use of sorghum for power generation is strongly affected by (I) the high moisture content at harvest time (Quaranta *et al*., 2009, Pari *et al*., 2011, Zagada-Lizarazu and Monti, 2012, Assirelli *et al*., 2013) and (II) the production risk of not achieving a determinate threshold of biomass necessary to fulfil the biomass needs of the power plant.

In Chapter 2 was described the results of our study on the dynamics of field drying of three genotypes of sorghum characterized by different earliness (early, medium-late and late). The analysis showed that the early sorghum genotype allows to reach the best trade-off between biomass production and moisture content at baling time. In Chapter 3, was explored the biomass production risk by estimating the number of hectares necessary to plant sorghum in order to cover the biomass needs of the power plant and by defining the cumulative probability to exceed a determinate biomass production threshold to satisfy the power plant needs.

This Chapter completes the two previous studies by analysing the environmental and energetic performance of a modelled biomass supply chain fed by three sorghum genotypes characterized by different earliness (early, medium-late and late) complemented by winter wheat (*Triticum aestivum* L.) straw fuelled to a direct combustion power plant.

Bioenergy is mostly promoted for climate change mitigation purposes. Nonetheless, in the last years, several studies have highlighted potential environmental risks that may, at best, require careful monitoring and, at worst, render bioenergy worse than fossil alternatives. Concerning energy crops grown on agricultural land, such as sorghum, the main concern is related to indirect land use change or iLUC. This is a market-mediated effect caused when a certain agricultural commodity is displaced from the food/feed market towards the energy market. In simplified terms, the overall agricultural market will respond to this shock in demand by increasing prices of the commodity displaced with the further consequence of an eventual partial decrease in the demand and a subsequent land use change to cropland with the associated GHG emissions. These indirect effects have the potential to increase the GHG emission associated with certain bioenergy feedstock (Marelli *et al*., 2011, Searchinger, 2008, Marelli *et al*., 2015).

Furthermore, other important direct environmental emissions associated to the production of dedicate bioenergy crops are due to soil nitrous oxide (N_2O) emissions, soil CO_2 and methane (CH_4) fluxes, and CO_2 emissions derived from agricultural inputs and agricultural machineries operations (Robertson *et al*., 2000, Del Grosso *et al*., 2001, West and Marland, 2002, Stehfest and Bouwman, 2006).

Finally, small-scale biomass combustion systems are known to usually cause higher emissions of local pollutants than large-scale fossil installations (Giuntoli *et al*., 2013; Giuntoli *et al*., 2015b).

In this chapter we perform a Life Cycle Assessment (LCA) of a bioenergy system where around 94.000 Mg DM y^{-1} are fed to a 50 MW_{th} biomass power plant. A long-term cropping system simulation (Chapter 3) provides the production yields and losses of sorghum for the last 39 years. The system is designed so that the missing production is complemented by winter wheat straw. The power plant is modelled according to a real plant project which is being evaluated in the area considered (Original approved technical details of sorghum power plant, 2012). Finally, the three genotypes of sorghum are tested.

Scientific literature has focused in the past years mostly on biomass sorghum used to produce ethanol (Köppen *et al*., 2009, Fazio and Monti, 2011, Cai *et al*., 2013, Olukoya *et al*., 2015), and used for biogas production (Agostini *et al*., 2015; Blengini *et al*., 2011), but to the authors' knowledge no scientific paper studying the environmental impact of biomass sorghum used for electricity generation by direct combustion.

On the contrary, the potential environmental impacts of the use of cereal straw for power generation have been studied in details (see for instance Giuntoli *et al*., 2013, Parajuli *et al*., 2014, Marelli *et al*., 2015); especially lately attention has been placed on the potential climate impact due to foregone sequestration of Soil Organic Carbon (SOC) when straw is combusted for energy (Giuntoli *et al*., 2016, Marelli *et al*., 2015; Monforti *et al*., 2015).

In this study: (I) we have modelled in details a potential bioenergy supply chain based on sorghum and wheat straw that could be implemented in the Po Valley to reconvert dismissed sugar factories; (II) we use the results from a cropping system model to assess the environmental impacts of the system for 39 years of activity and for three different sorghum genotypes and (III) we have performed an extensive sensitivity analysis to provide a broad spectrum of results under multiple assumptions. We believe that our work will contribute to fill the gap in the literature and will support decision makers by highlighting potential environmental red flags.

4.2 Materials and Methods

This LCA was performed according to the ISO 14040 and 14044 standards (ISO, 2006a,b), using the software Gabi 6.3, from Thinkstep, (2015). This work is divided in three sections. In Section 4.2.1 the goal and the scope of the assessment are defined. In Section 4.2.2 we present the Life Cycle Inventory (LCI) in details. In Section 4.3 we present the results and the discussions obtained according to the scheme provided by the ISO standards. Finally Section 4.4 the conclusions of the study are summarized.

4.2.1 Goal and scope definition

The main goal of this study is to compare in a long-term simulation of the last 39 years (detailed in Chapter 3), the potential environmental impact and energy performance of a biomass supply chain fed by three sorghum genotypes characterized by different earliness (early, medium-late and late). In the simulated years in which the production of biomass sorghum was not sufficient to fully cover the biomass needs of the power plant, winter wheat straw was considered to complement the sorghum.

To produce biomass from sorghum cultivation, a mosaic of virtual farms was simulate (see Chapter 3) equally distributed around two focus centres: the biomass power plant (45°00’N, 8°54’E) and a satellite storage facility (SSF), where biomass is temporary stored before being transported to the power plant, located 25 km from the power plant (45°08’N, 9°21’E) in the Po Valley.

The environmental impacts analyzed are listed in Table 4.1 and the characterization models were chosen according to the ILCD, (2010) recommendations and they were implemented in Gabi 6.3 software (Thinkstep, 2015).

The assessment is performed at midpoint using the methods recommended by the ILCD Handbook (IES, 2012).

Table 4.1 - Impact categories analyzed in this study. In addition, are shown the characterization model and the category indicator result.

Impact category	Characterization Model	Category indicator result
Global Warming potential	IPCC 5th Assessment report, 2013. Global Warming potentials (GWP) at 100-year time horizon. Climate feedbacks included.	kg CO_2 $_{eq.}$
Acidification potential	Accumulated exceedance	mol H^+ $_{eq.}$
Particulate matter	RiskPoll	kg PM2.5 $_{eq.}$
Photochemical Ozone Formation	LOTOS-EUROS model	kg NMVOC $_{eq.}$
Freshwater eutrophication potential	ReCiPe 1.08 Midpoint (H)	kg P $_{eq.}$
Marine eutrophication potential	ReCiPe 1.08 Midpoint (H)	kg N $_{eq.}$
Energy Return on Energy Investment	Primary Energy from non renewable resources (on LHV basis)	MJ

We consider that the sorghum productivity is dynamic in time over 39 years, however, all other assumptions, background data and emission factors are considered to be static. The results over the 39 years thus aim to represent more of a probabilistic distribution rather than a detailed historical description or forecast.

Primary data collected in the scope of this research were complemented with secondary data from literature and from commercial LCA databases (Ecoinvent 2.2, 2010 and Thinkstep Professional 2015).

4.2.1.1 Functional unit and system boundaries

The study considers "cradle to grave" boundaries and the functional unit considered is 1 MJ of electricity generated at the power plant outlet.

Fig. 4.1 summarizes the system boundaries of the study. The sorghum production pathway is divided into the following processes: sorghum cultivation, transport and energy conversion. "Sorghum cultivation" process is composed from all input and emissions involved from soil preparation to sorghum bales loading; "Transport" process takes into consideration all inputs and emissions of the transport options and "Energy Conversion" process considered input and emissions regarding energy production by direct biomass combustion in the power plant and flue gas cleaning.

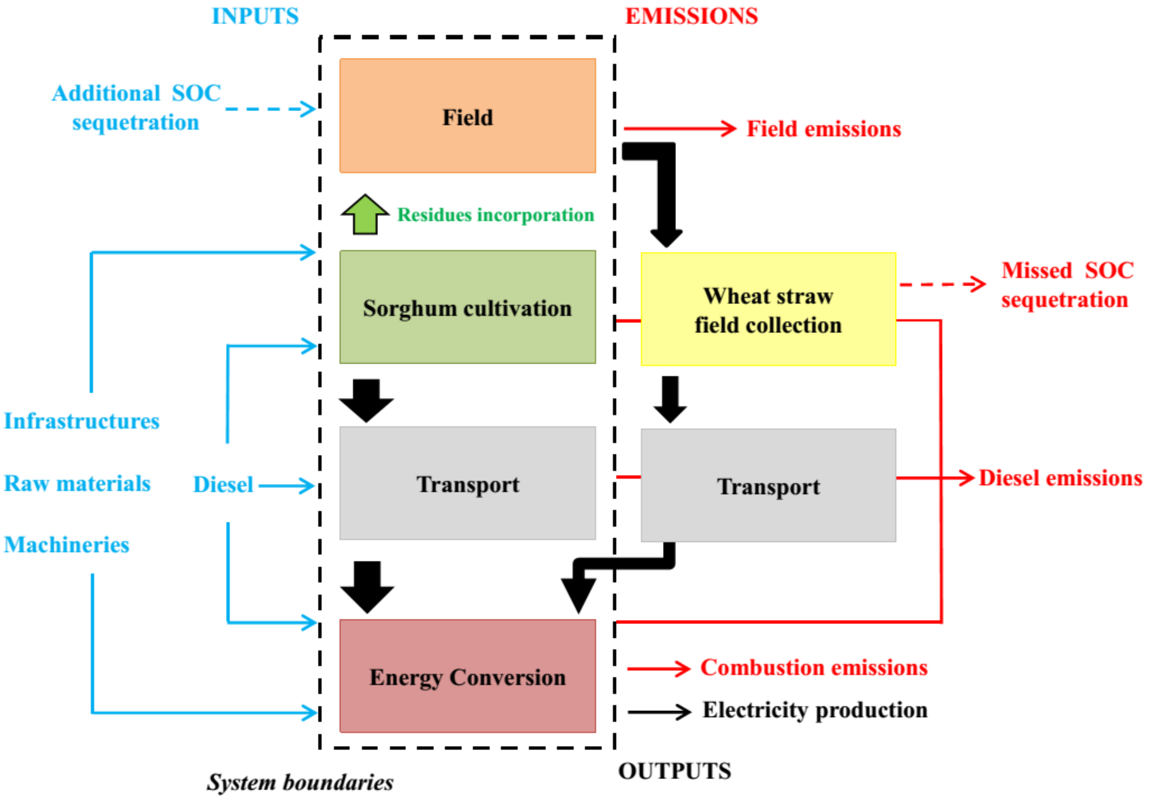


Fig. 4.1 - Schematic flowchart of the "cradle to grave" system. In blue are indicated the inputs, in red the emissions and in green the output of the system. The black dotted line symbolizes the system boundaries while blue and red dotter line represent the additional SOC from sorghum residues and the missed SOC sorghum due straw removal, respectively.

We considered that the reference system comprises sugar beet cultivation and harvest (at regime) and the incorporation of wheat straw in the soil. Thus in the bioenergy system: (I) the substitution of sugar beet with sorghum creates a demand shock requiring the inclusion of an iLUC factor; (II) in case of additional sorghum losses, due to mechanical limitations or to haymaking failure, an increase in the stock of soil organic carbon (SOC) in the cropland considered (Fig. 4.1 blue dotter line); (III) the removal of wheat straw is associated to a decrease in SOC stock, a decrease in N_2O emissions as well as a potential need for compensation of removed nutrients (Fig. 4.1 red dotter line).

Straw is considered as a residue from the wheat grains cultivation and no allocation of upstream emissions is accounted.

4.2.2 Life cycle inventory (LCI)

Life Cycle Inventory (LCI) was compiled with primary data from field operations, agricultural machineries characteristics and fuel consumption obtained in experimental field trials performed in 2010 and 2012 in the Po Valley, northern of Italy (for details see Chapter 2 and Chapter 3). To implement and verify the reliability of the data collected they were compared with the data derived from the respective agricultural machineries manufacturers. In addition, the datasets collected were complemented by commercial databases (Ecoinvent 2.2, 2010 and Thinkstep Professional, 2015) for background processes.

4.2.2.1 Sorghum cultivation and straw collection inputs

Table 4.2 lists in details the quantity and types of material inputs for the cultivation of the sorghum genotypes. The three sorghum genotypes received the same field treatments.

Yearly biomass production of the three sorghum genotypes was simulated through CropSyst model (Stöckle *et al.*, 2003) and the results are presented in Chapter 3. The model was calibrated and validated on a medium-late earliness sorghum genotype (Biomass 133 commercialized by Syngenta) with production data collected in mid-term experimental trials in the Po Valley between 2006 and 2010 (as reported in Chapter 2). The simulations considered a period of 39 years (from 1976 to 2014). The CropSyst model was coupled to a specific model, "sorghum haying model", to simulate the dynamic of sorghum field drying process (Chapter 2) and to calculate biomass lost due to mechanical and respiration losses and haymaking failure (Chapter 3) and consequently quantify the biomass baled available to be transported to the power plant. Field equipment commonly used for fodder crops was adopted to harvest and collect biomass sorghum. It consists of a work chain composed by: cutting, tedding, windrowing and collecting in accordance to Assirelli *et al.*, (2013). The obtained prismatic bales had a weight approximately of 450 kg (23%$_{\text{wb}}$ moisture content), dimensions of 2.2 x 1.2 x 0.7 m and volume of 1.85 m^3. The bales were secured with 6 knotted plastic twines; these are the most common wrapping systems for forage and straw in the area. Straw collection was performed using the same agricultural machinery (tractors and equipment) involved in the sorghum collection assuming a moisture content of 14%.

Table 4.3 lists the details for all field operations both for biomass sorghum and straw; in addition the characteristics related to the agricultural machineries used are also reported.

The amount of straw, necessary to complement biomass sorghum in full covering biomass power plant, was calculate with the following Equation (4.1):

$$Quantity\ of\ straw\ (Mg\ DM\ y^{-1}) = T.biomass - (SB * ha) \tag{4.1}$$

whereby *T. biomass* represents the yearly amount of biomass necessary to cover biomass power plant needs (94000 Mg DM y^{-1}); *SB* is the yearly biomass sorghum production yearly simulated with CropSyst model (Mg DM ha^{-1} y^{-1}) and *ha* represents the amount of hectares necessary to plant biomass sorghum, as defined in Chapter 3, amounting to 4221.6 hectares.

Table 4.2 - Sorghum cultivation and straw collection inputs. Data were collected from experimental trials in time period from 2010 and 2012 and completed by commercial and literature database.

Elements	**Unit**	**Sorghum genotype**			**Straw**	**Comments**
		Early	**Medium-late**	**Late**		
Sorghum seeds	kg $ha^{-1}yr^{-1}$	10	10	10	/	
Fertilizer urea as N	kg $ha^{-1}yr^{-1}$	80	80	80	/	
Fertilizer triple phosphate as P_2O_5	kg $ha^{-1}yr^{-1}$	60	60	60	/	
Herbicides	kg/ha a.s.[a]	1.50	1.50	1.50	/	S-Metolaclor, Terbutilazina
Plastic wraps and twine	kg $ha^{-1}yr^{-1}$	35.92	35.92	35.92	25.90	For recover and tie big balers
Machinery	kg $ha^{-1}yr^{-1}$	2.93	2.93	2.98	1.25	Only agricultural tractors
Machinery	kg $ha^{-1}yr^{-1}$	3.73	3.75	3.80	2.18	Only agricultural machinery
Machinery shed	$m^2ha^{-1}yr^{-1}$	0.01	0.01	0.01	0.001	Only for agricultural machinery (average lifespan 40 years)
Diesel fuel	kg $ha^{-1}yr^{-1}$	102.90	102.90	102.90	11.57	Only for sorghum cultivation and straw baling
Diesel fuel	kg $ha^{-1}yr^{-1}$	26.57	29.14	34.08	/	Only for sorghum harvest
Diesel fuel	kg $ha^{-1}yr^{-1}$	13.86	12.89	13.17	4.41	Only for biomass field loading (average value)
Lubricating oil	kg $ha^{-1}yr^{-1}$	0.41	0.41	0.42	0.03	For agricultural machineries (tractors and equipments) included disposal
Lorry trasport	t km yr^{-1}	10.69	10.73	10.86	12.22	For purchased raw materials (for sorghum cultivation and straw collection)

[a] a.s. = active substance

Table 4.3 - Biomass sorghum field operations from soil tillage to bales transport. The marker † indicated the agricultural machinery involved also in the straw collection and transport.

Operation	Weight (Kg)		Power (Kw)	Lifespan (hours)		Type of machinery	Comments
	Machinery	Tractor	Tractor	Machinery	Tractor		
Plowing by mounted reversible plough	1150	7900	164	2500	12000	Kuhn multi-master 113 NSH	four bodies, working with 1.6 m
Harrowing by tandem disk harrow	4420	7900	164	2500	12000	Kuhn ODH 5800-17	four disk arms working with: 4 m
Fertilising by fertiliser spreader	400	6400	110	1200	12000	Kuhm AXIS 40.2 M-EMC W	twin disc, working with: 20 m
Harrowing by power harrow	2116	7900	164	2500	12000	Lenmken Zirkon 12/500K	twenty rotors, working with: 5 m
Sowing by pneumatic drill	875	6400	110	1500	12000	Gaspardo SP Dorata	six raw, working with: 4.2 m
Weeding by mounted agricultural sprayer	1000	6400	110	1500	12000	Kuhn Deltis 800-1200	working with: 20 m
Hoeing and N fertilization by row crop cultivator	930	6400	110	2000	12000	MaterMacc UNICA-PVI	six rows, working with: 3.4
Harvesting by mower conditioner	1400	7900	164	2000	12000	Prototype CRA-ING Cressoni	width cutter bar: 2.8 m
Teddering by rotary rake tedder	980	6400	110	2500	12000	Claas Volto 800	six rotary, working width: 7.70 m
Windrowing by rotary windrower	1900	6400	110	2000	12000	Claas Liner 2700	twin rotary, working width: 7.20 m
Baling by large square baler†	9000	7900	164	2000	12000	Krone Big Pack HS 1290	pick up with: 1.2 m
Bales field loading by front loader†	450	6400	110	3000	12000	Fendt Cargo 4X75 Compact	fork with three tines, with 1.5 m
Transport bale biomass by agricural machinery†	4550	7900	164	3000	12000	Pagliari PB 146	three axes, payload capacity 14 ton
	29171	92200	1754	28200	156000		

When straw is removed, we considered that additional mineral fertilizer should be applied to compensate the nutrients removed in accordance to Schmidt *et al.*, (2013). For this reason, the equivalent amount of fertilizers to reintegrate straw removal was calculated based on the elements removed with the straw in the form of Nitrogen (N), Phosphorous (P) and Potassium (K). The fertilizers considered to compensate straw removal, were urea (46%), triple phosphate (45%) and potassium chloride (60%). The amount of fertilizers was calculated through a linear interpolation of the yearly straw quantity necessary to cover power plant needs.

4.2.2.2 Field emissions from sorghum cultivation and straw collection

Field emissions are associated to the mineral fertilization and to the decomposition of above and belowground sorghum residues. N fertilization consists of application of urea in the quantity of 80 kg ha^{-1}, responsible for the emissions of nitrous oxides, nitrogen oxide and ammonia. Indirect nitrous oxides emissions are calculated for ammonia and in according to IPCC, (2006); NO_x emissions are calculated according to Stehfest and Bouwman, (2006) and N_2O from nitrate leaching is calculated according to IPCC, (2006).

Direct N_2O emissions, from urea application and from annual above and belowground biomass sorghum residues were calculated in according to IPCC, (2006).

In this study the phosphate run-off to surface water, deriving from application of 60 kg ha^{-1} of triple phosphate, was estimated to be 0.201 kg $P_{run\text{-}off}$ ha^{-1} y^{-1} per kg P from fertilizer, in accordance to Prasuhm, (2006). The emission values from above-belowground residues and leaching are variable in the 39 years considered, because linked to the biomass sorghum production and losses level.

As mentioned earlier, since we considered the reference system to include wheat straw incorporation in the soil, when straw is used for bioenergy, we need to account for the foregone sequestration of soil organic carbon (SOC), i.e. additional CO_2 emissions for the bioenergy feedstock.

A triennial crop rotation composed by winter wheat, soybean and biomass sorghum was simulated over the long-term of 39 years using the CropSyst model with default parameterisation for winter wheat and soybean, while using the same calibrated validated parameters for biomass sorghum used in Chapter 3.

For the purpose of quantifying the effect of straw removal on SOC content, we simulated, for each year, two scenarios: 1st) straw removed (5 cm of wheat stems were left on field); 2nd) straw incorporated into the soil with ploughing. ΔSOC was simulated in three representative soil types present in the sorghum supply area (ISN1, CCO1 and VIC1) characterized by different agronomic characteristics (for more information see Chapter 3)

Both scenarios we considered a straw production of 5 Mg DM ha^{-1} in accordance to the average straw production in the studied area. The additional CO_2 emission factor associated to the wheat straw feedstock resulted to be equal to 0.15 kg CO_2 kg^{-1} dry straw (see Annex 1 for details over this calculation). In a first approximation, the eventual increase in SOC stock for sorghum incorporation was considered to be of the same amount. Since this is a very relevant parameter in the overall GHG balance, we have tested various alternatives and the results are presented in the sensitivity analysis.

The avoided N_2O emissions due to straw removal were calculated starting from straw nitrogen content (Deimling and Rehl, 2010) and using a specific emission factor (IPCC, 2006). This was showed in Equation (4.2).

$$Avoided\ nitrogen\ straw\ emissions\ (kg\ N_2O\ ha^{-1}) = SP*N*EF*(N_2O/N_2) \tag{4.2}$$

whereby: *SP* is the yearly dry matter straw production (Mg DM ha^{-1}); *N* is straw nitrogen content expressed in kg N kg^{-1} straw (we used 0.0065), *EF* represent the emission factor in according to IPCC, (2006) and N_2O/N_2 is stoichiometric ratio between nitrous oxide and nitrogen.

4.2.2.3 Biomass production: diesel consumption

Tractors fuel consumption was calculate considering the following four categories:

- diesel consumed during field operations involved in the sorghum cultivation stage;
- diesel consumed during sorghum harvest operations;
- diesel consumed during field biomass bales loading;
- diesel consumed during bales transport to the biomass power plant and to the storage satellite facility (SSF) with agricultural machineries.

The diesel consumption, excluding diesel used during harvesting operations, was estimated by the determination of fuel consumption according to Fröba and Funk, (2004), Equation (4.3):

$$Diesel\ consumption\ \left(kg\ ha^{-1}\right) = P * Sc * Tw * dd \tag{4.3}$$

whereby P is the tractor power expressed as kW, Sc is the specific diesel consumption of the tractors expressed as kg kWh^{-1}, *Tw* is the working time required expressed as h ha^{-1}, and *dd* is the density of diesel fuel expressed in kg $^{-1}$.

The values for specific diesel consumption (*Sc*) were taken from the German Agricultural Society (DLG).

The working time (*Tw*) for each field operation, was calculated according to Lubbe *et al*., (2013) using the following Equation (4.4):

$$Tw\ (h\ ha^{-1}) = \frac{1000}{Ww * Ws * 1000} * Eff \tag{4.4}$$

whereby Ww is the work width of agricultural machineries expressed as m, Ws is the work speed as km h^{-1} and Eff is the effectiveness of the machineries (ASABE, 2006).

To increase the reliability of the study, the diesel used during harvesting operations was estimated proportional to the quantity of biomass sorghum produced in the 39 simulated years.

The diesel used during biomass bales field loading was estimated starting from the number of biomass bales obtained in each simulated year while, the diesel used during biomass bales transport was calculated taking into account the carrying capacity of the trailer and the distance between virtual farms-power plant and between virtual farms-power plant (see Section 4.2.2.4 and 4.2.2.5).

The total amount of engine and hydraulic oil needs during the lifetime of the agricultural machineries was calculated according to Ammann and Stadler, (1998).

4.2.2.4 Creation of a road network for biomass transport

In this study was assumed the use of an intermediate storage satellite facility (SSF) to collect and store biomass bales according to the plant storage capacity. This is assumed to be located 25 km from the power plant in the Po Valley.

In Chapter 3 was created a mosaic of 486 virtual farms located in the sorghum supply area. Starting from the geographic location, of each virtual farms, and take into account also of the geographic location of biomass power plant (45°00'N, 8°54'E) and of the SSF (45°08'N, 9°21'E) a dataset of shortest straight travel distance was created. The maximum distance found from virtual farms to biomass power plant was 57 km and from virtual farms to SFF was 68 km. These distances are in accordance to Hamelinck *et al*, (2009) that reported a maximum distance for biomass road transport of 100 km.

During the planning stage of the biomass transport, the complexity of real road network is a critical factor to take in consideration and the estimation of a tortuosity factor (τ) is fundamental to increase the reliability of the study (Sultana and Kuman, 2014). The τ factor was calculated as the ratio between the shorter straight line distance of 20 real fields involved in an experimental trials performed in 2010 in the Po Valley (see Chapter 2) and the respective actual travel distances computed by Google Maps.

The calculated (τ) factor of 0.75 was applied to the shortest straight travel distance to estimate the real travel distances via the road network from the biomass collection points (virtual farms and SSF) to the biomass power plant.

4.2.2.5 Biomass transport options

After baling, bales are transported to the power plant or to the SSF based on the distance between the virtual farm and the power plant (D1), the distance between the virtual farm and the SSF (D2) and according to the storage capacity of the power plant. In particular, the bales were transported to the power plant when D1<D2*SC, where SC is a storage coefficient that depends on the storage capacity of the power plant. This function favours the direct transport of biomass to the power plant until its storage capacity is completed and in this case study it was assumed a storage capacity of 40.000 Mg DM for which SC=2.05.

Two bales biomass transport options were considered: the use of conventional trucks or agricultural machinery (tractor and trailer combination).

The condition to choose agricultural machinery or conventional trucks was the following: if the distance D1 was less than D2 multiplied by SC, biomass bales were transported directly to the biomass power plant; otherwise the bales were transported to the SSF and subsequently from this to the power plant in accordance to the power plant needs.

To cover travel distance D1 and D2, a fixed-bed trailer pulled by a 164 kW tractor was used. The net payload capacity was 14 ton, corresponding to 31 bales both of sorghum and straw transported at 23% and 14% of moisture content, respectively.

At the SSF, the bales were stacked in stacks by a loader front mounted at 110 kW tractor stacking one bale at a time. To preserve biomass from rain and to reduce dry matter losses, the bales were stacked on discharged pallets to avoid contact with the ground and covered with plastic traps.

After storage in the SSF, the bales were transported to the power plant using a flatbed truck and trailer with the gross weight of 28-34 ton and 22 ton of net payload capacity, corresponding to 48 bales transported. The payload is considered to be weight limited and thus fully utilized by the bales load. Both for sorghum and straw bales transported by truck, a moisture content of 14% was assumed and an utilization factor of 0.85 was used to account for the return trips of the trucks with empty or partial load.

The inventory of the transport process was taken from the Thinkstep Professional database, (2015). The chosen dataset for the diesel describes a mass-weighted average refinery diesel from crude oil for Europe (EU-27) and is taken from the Thinkstep Professional database, (2015). The output of the process are the emissions from diesel combustion.

The diesel emission factors for sorghum cultivation, straw collection and transport are taken from EMEP/EEA Inventory Guidebook, 2013. Data from several literature sources were used in order to calculate these emissions and the details are shown in Table 4.4 for sorghum and Table 4.5 for straw.

4.2.2.6 Energy conversion: power plant characteristics

The biomass power plant modelled in this work is considered to have a thermal capacity of 49.95 MW_{th} input with a gross capacity of 15 MW_{el}. We considered it to be an electricity-only plant according to the technical power plant design (Original approved technical details of sorghum power plant, 2012). We assume that the net efficiency (η_e) of conversion is the same for sorghum and straw bales combustion and that is equal to 20.5 %.

The total amount of biomass (Mg DM y^{-1}) necessary to cover the plant requirements is 94000 Mg DM y^{-1}. The sorghum share is different each year in relation to the sorghum yield, while the straw share is complementary to sorghum share.

The total amount of biomass requirement was calculated following the Equation (4.5):

$$Total\ biomass\ (Mg\ DM\ y^{-1}) = \frac{(MW_{\mathrm{th}} * 3.6) * H)}{LHV_{14\%}} * (1 - Moisture) \qquad (4.5)$$

whereby MW_{th} is the thermal capacity of the plant, *3.6* is the conversion factor from MW_{th} to GJ_{th}, H is the number of yearly work hours (8000) of the plant, $LHV_{14\%}$ is the lower heating value (13.186 MJ kg^{-1}) at 14% of moisture content assumed equal for sorghum and straw.

The lower heating value dry (LHV_{dry}) of sorghum and straw is assumed to be 15.73 MJ kg^{-1} and it was calculated starting from $LHV_{14\%}$ following the Equation (4.6):

$$LHV_{dry} = \frac{LHV_{14\%} + (2.441 * Moisture)}{(1 - Moisture)} \qquad (4.6)$$

Biomass power plant storage platforms are composed by 12 sheds with a total area of 40.120 m^2 able to storage approximately 40000 Mg DM y^{-1}.

At the biomass power plant the stacking of bales is performed using four telescopic handlers: three used to manage bales in the storage area and one to load the power plant conveyor belt. All telescopic handlers carry two bale at a time.

The diesel consumption and emissions, lubricating oil consumption and power plant infrastructures are included and estimated on MJ in input.

The diesel consumption and emissions, lubricating oil consumption and power plant infrastructures are included and estimated on MJ in input.

Pollutants' emissions control was performed with the following equipment: two cyclones, bag filter and $DeNO_x$ Selective No Catalytic Reaction (SNCR) system.

Table 4.4 - Diesel consumptions and emissions for each field operations involved in the production of biomass sorghum. [†]Average diesel consumption related to early, medium-late and late genotype; [††] bales transport from virtual fields to biomass power plant (average distance 24.5 km); [†††] bales transport from virtual fields to SSF (average distance 16 km). The average distance takes into account the loading and unloading trips of agricultural machinery.

Field operations	**Diesel consumption (kg ha^{-1} y^{-1})**	**Diesel emissions (kg of element per Mg $diesel^{-1}$ ha^{-1} y^{-1})**									
		CH_4	**C0**	**$C0_2$**	**N_20**	**NH_3**	**NMVOC**	**NO_X**	**PM10**	**PM2.5**	**TSP**
Plowing by mounted reversible plough	36.7	0.0020	0.4019	116.0961	0.0050	0.0003	0.1237	1.2875	0.0639	0.0639	0.0639
Harrowing by tandem disk harrow	12.9	0.0007	0.1407	40.6337	0.0017	0.0001	0.0433	0.4506	0.0223	0.0223	0.0223
Fertilising by fertiliser spreader	1.5	0.0001	0.0163	4.7005	0.0002	0.0000	0.0050	0.0521	0.0026	0.0026	0.0026
Harrowing by power harrow	14.6	0.0008	0.1594	46.0515	0.0020	0.0001	0.0491	0.5107	0.0253	0.0253	0.0253
Sowing by pneumatic drill	9.7	0.0005	0.1065	30.7771	0.0013	0.0001	0.0328	0.3413	0.0169	0.0169	0.0169
Weeding by mounted agricultural sprayer	1.7	0.0001	0.0184	5.3031	0.0002	0.0000	0.0056	0.0588	0.0029	0.0029	0.0029
Hoeing and N fertilization by row crop cultivator	10.5	0.0006	0.1152	33.2664	0.0014	0.0001	0.0354	0.3689	0.0183	0.0183	0.0183
Harvesting by mower conditioner[†]	29.9	0.0016	0.3274	94.5788	0.0041	0.0002	0.1007	1.0488	0.0520	0.0520	0.0520
Teddering by rotary rake tedder	3.7	0.0002	0.0407	11.7513	0.0005	0.0000	0.0125	0.1303	0.0065	0.0065	0.0065
Windrowing by rotary windrower	4.0	0.0002	0.0435	12.5673	0.0005	0.0000	0.0134	0.1394	0.0069	0.0069	0.0069
Baling by large square baler	7.6	0.0004	0.0830	23.9851	0.0010	0.0001	0.0255	0.2660	0.0132	0.0132	0.0132
Bales field loading by front loader[†]	13.3	0.0007	0.1455	42.0280	0.0018	0.0001	0.0448	0.4661	0.0231	0.0231	0.0231
Transport bale biomass by agricural machinery[††]	27.8	0.0015	0.3038	87.7532	0.0038	0.0002	0.0935	0.9731	0.0483	0.0483	0.0483
Transport bale biomass by agricural machinery[†††]	18.1	0.0010	0.1979	57.1644	0.0025	0.0001	0.0609	0.6339	0.0314	0.0314	0.0314
Sum	192.0	0.0106	2.1001	606.6565	0.0261	0.0015	0.6462	6.7276	0.3337	0.3337	0.3337
Average	13.7	0.0008	0.1500	43.3326	0.0019	0.0001	0.0462	0.4805	0.0238	0.0238	0.0238

Table 4.5 - Diesel consumptions and emissions for each field operations involved in the collection of straw. †Straw bales transport was assumed the same of biomass sorghum.

Straw operations	**Diesel consumption (kg ha^{-1} y^{-1})**	**Diesel emissions (kg of element per Mg diesel^{-1} ha^{-1} y^{-1})**									
		CH_4	**C0**	**$C0_2$**	**N_20**	**NH_3**	**NMVOC**	**NO_X**	**PM10**	**PM2.5**	**TSP**
Baling by large square baler	7.6	0.0004	0.0830	23.9851	0.001	0.0001	0.0255	0.2660	0.0132	0.0132	0.0132
Bales field loading by front loader	9.7	0.0005	0.1061	30.6520	0.001	0.0001	0.0327	0.3399	0.0169	0.0169	0.0169
Transport bale biomass by agricural machinery†	27.8	0.0015	0.3038	87.7532	0.0038	0.0002	0.0935	0.9731	0.0483	0.0483	0.0483
Transport bale biomass by agricural machinery†	18.1	0.0010	0.1979	57.1644	0.0025	0.0001	0.0609	0.6339	0.0314	0.0314	0.0314
Sum	63.2	0.0035	0.6908	199.5547	0.009	0.0005	0.2126	2.2130	0.1098	0.1098	0.1098
Average	15.8	0.0009	0.1727	49.8887	0.0021	0.0001	0.0531	0.5532	0.0274	0.0274	0.0274

NO_x emissions are a serious concern especially in the area of the Po Valley where special regulations exist to impose strict emission limit values on any new installation. To achieve such limits even small-scale biomass plants require the use of $DeNO_x$ (SNCR) systems. However, while the SNCR equipment is able to reduce NO_x emissions by 40% (Original approved technical details of sorghum power plant, 2012), the de-NO_x reaction with urea does not produce only molecular nitrogen but also other by-products such as NH_3 and N_2O. In order to highlight this potential burden shifting, we have modelled the products of the $DeNO_x$ reaction at equilibrium at a temperature between 850-900°C (Mendoza-Covarrubias *et al.*, 2011). These values are included in the inventory of combustion emissions reported in Table 4.6.

However, we acknowledge that actual conditions in the reactor will be very different from equilibrium and may produce very different emission products. We test this assumption in the sensitivity analysis by considering a plant without SNCR.

Biomass power plant combustion emissions are taken mainly from Giuntoli *et al.*, (2013) and are suitable for biomass power plants with a maximum power output of 25 MW_{el}, which is comparable with the plant modelled in this work.

We assumed ash-forming-matter content in biomass of $7.02\%_{wb}$, according to Jenkins *et al.*, (1998). The disposal of ashes is considered into the boundaries of this study.

4.2.2.7 iLUC emission factor

According to Fritsche, (2008) the indirect land use change (iLUC) occurs when land currently used for feed or food crops is changed into bioenergy feedstock production and the demand for the previous land use (i.e. feed, food) remains, because the displaced agricultural production will move to other places where unfavourable land use change could occur.

In order to strictly apply the latest science and understanding of the issue, we included in our model an iLUC CO_2 emission factor for the displacement of sugar beet to energy crop. However, the case considered in this work is peculiar: the cropping change from a food crop to an energy crop is not the result of bioenergy policies but rather it is sparked by another European Regulation (318/2006/EC) and thus one could argue whether this emission penalty should be allocated to the bioenergy system. For this reason, we present results with and without this emission factor.

We calculated the iLUC emission factor starting from the iLUC carbon emissions (CO_2 MJ ethanol^{-1}) of bioethanol production from sugar beet provided by Laborde *et al.*, (2011). The value included in our inventory is equal to 947.03 kg CO_2 ha^{-1}.

Table 4.6 - Emission factors for the biomass power plant including a $DeNO_x$ SNCR equipment.

Parameter	Unit	Value	Source
Net electrical efficiency	%	20.5	Original approved technical details of sorghum power plant (2012)
NH_3*	Kg	1.13E-05	/
CO	Kg	6.70E-05	Nielsen *et al.* (2010)
SO_2	Kg	4.90E-05	Nielsen *et al.* (2010)
HCl	Kg	5.60E-05	Nielsen *et al.* (2010)
CH_4	Kg	4.70E-07	Nielsen *et al.* (2010)
N_2O**	Kg	5.00E-05	Nielsen *et al.* (2010)
NO_x***	Kg	1.61E-05	Nielsen *et al.* (2010)
NMVOC	Kg	7.80E-07	Nielsen *et al.* (2010)
Dust (>PM 10)	Kg	1.12E-04	Ecoinvent (2010)
Dust (PM 2.5)	Kg	2.30E-06	Nielsen *et al.* (2010)
Polychlorinated dibenzo-p-dioxins and furans (equivalent) (PCDD/-F)	Kg	1.90E-15	Nielsen *et al.* (2010)
Naphthalene	Kg	1.21E-08	Nielsen *et al.* (2010)
Hexachlorobenzene (HCB)	Kg	1.10E-13	Nielsen *et al.* (2010)
Benzo[a]pyrene (equivalent)	Kg	1.25E-10	Nielsen *et al.* (2010)
Cd†	Kg	3.20E-10	Nielsen *et al.* (2010)
Hg†	Kg	3.10E-10	Nielsen *et al.* (2010)
Zn	Kg	4.10E-10	Nielsen *et al.* (2010)

* Derives from calculations of $DeNO_x$ reaction products.

** Considers additional amount from $DeNO_x$ reaction products.

*** Considers a DeNOx abatement efficiency of 40%.

†All measurements below detection limit.

4.2.2.8 Sensitivity analysis

To test the effect of the many assumptions defined in the model set-up, we performed a sensitivity analysis over several parameters. This broad spectrum of results and scenarios will allow a better understanding and will provide a more effective support to decision-makers.

Specifically, we have tested the changes in environmental impacts with the following variations:

- Power plant without $DeNO_x$ SNCR equipment;
- iLUC emissions are not assigned to bioenergy;

- SOC accumulation rate from sorghum residues is different (higher/lower) from the value used for wheat straw;
- SOC accumulation rate is higher/lower than in the base case;

2.2.9 Emissions allocation

In the years in which biomass sorghum exceed the total biomass need (94000 Mg DM y^{-1}), creating a surplus, the emissions were allocated to the following years.

2.10 Fossil comparators

For illustrative purposes, we present the environmental impacts from other fossil systems to compare the results from the bioenergy system modelled. The values for the fossil systems are taken from Thinkstep Professional database, (2015). When assessing GHG emissions, we also present the Fossil Fuel Comparator for electricity defined by the European Commission (SWD/259, 2014 and Giuntoli *et al.*, 2015a).

4.3 Results and Discussions

4.3.1 Life cycle impact assessment (LCIA)

Fig. 4.2 shows the results for all the environmental impacts assessed in the form of boxplots depicting the statistical distribution over the 39 years simulated, for the three genotypes in the base case.

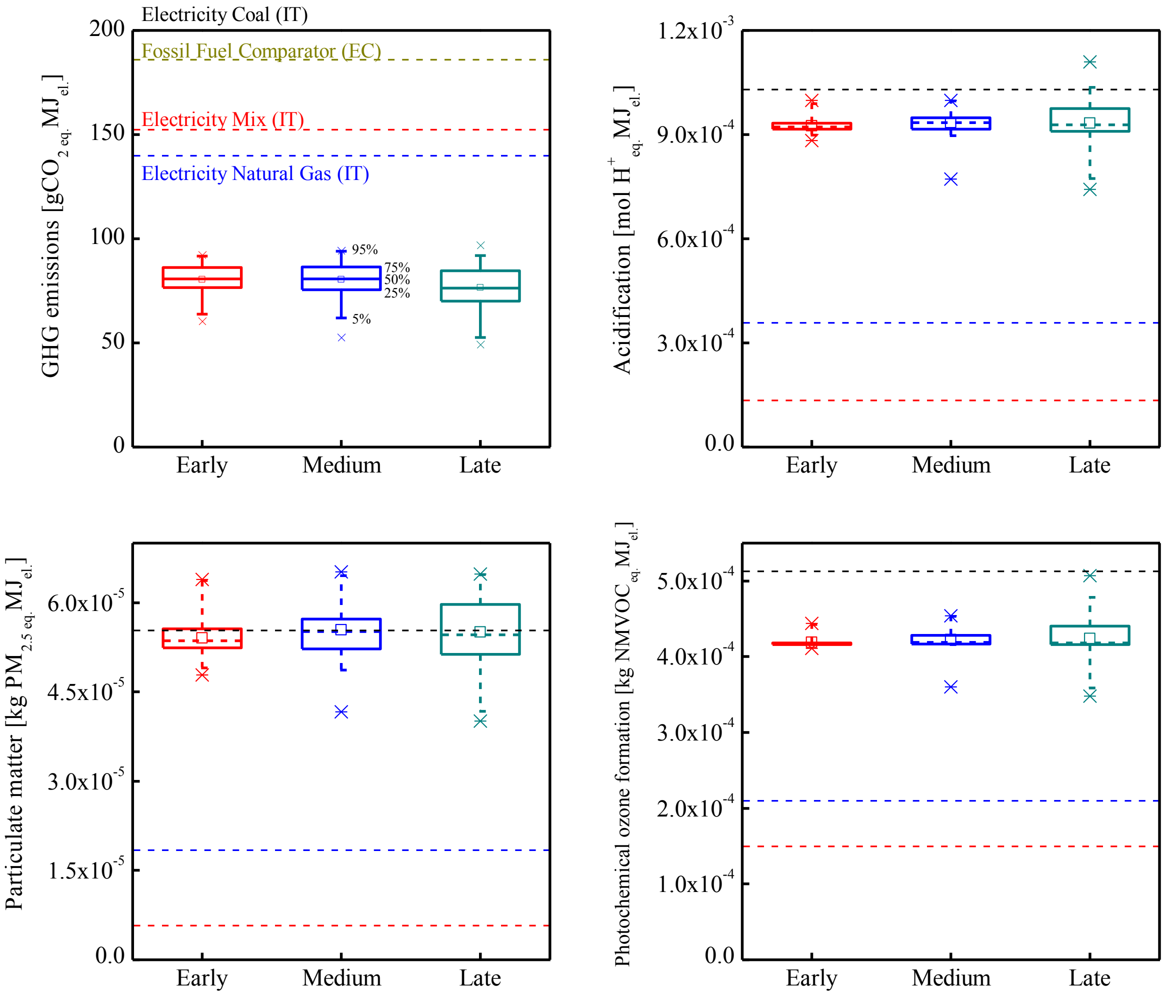
4.3.2 Global Warming Potential (GWP)

The average GHG emissions value of early genotype was calculated to be 80.52 g $CO_{2eq.}MJ^{-1}{}_{el.}$ and ranged from 60.34 to 92.14 g $CO_{2eq.}MJ^{-1}{}_{el.}$.The average GHG emissions value of the medium-late genotype was calculated to be in average 80.43 g $CO_{2eq.}MJ^{-1}{}_{el.}$ and ranged from 52.59 to 94.25 g $CO_{2eq.}MJ^{-1}{}_{el.}$. The average GHG emissions value of late genotype was calculated to be in average 76.58 g $CO_{2eq.}MJ^{-1}{}_{el.}$ and ranged from 49.15 to 96.83 g $CO_{2eq.}MJ^{-1}{}_{el.}$.

The late genotype thus appears to have lower average emissions and a wider spread throughout the years, although only the very maximum value is higher than the emissions for the other two genotypes. In all other cases the late genotype performs equal or better than the others.

In terms of GHG emissions, the base case considered represents a rather conservative situation since iLUC emissions are included and N_2O emissions from the SNCR are rather high. Nonetheless, on average and even the highest values measured are still lower than the fossil comparators. For instance, on average the late genotype is 45% lower than a natural gas pathway and 59% lower than the EU fossil fuels consumption. The highest value obtained would be about 68% lower than the GHG emissions from a hard coal plant. Fig. 4.3 and Fig. 4.4 present the contributional analysis by process and species for all the environmental impacts assessed. Since the spread across genotypes and across years appears to be limited, we only present the case for Medium genotype and median years. The main contributor to the GHG emissions is represented by CO_2 (64%) followed by N_2O (34%), CH_4 (2%).

In terms of processes, the power plant (23%) is the process that more contributes to the GHG emissions followed by SOC decrease due to straw removal (18%) and iLUC plus agricultural diesel (11%). The emission credits for SOC accumulation due to sorghum residues accounts for -11% and another -5% derives from avoided N_2O emissions for straw removal.



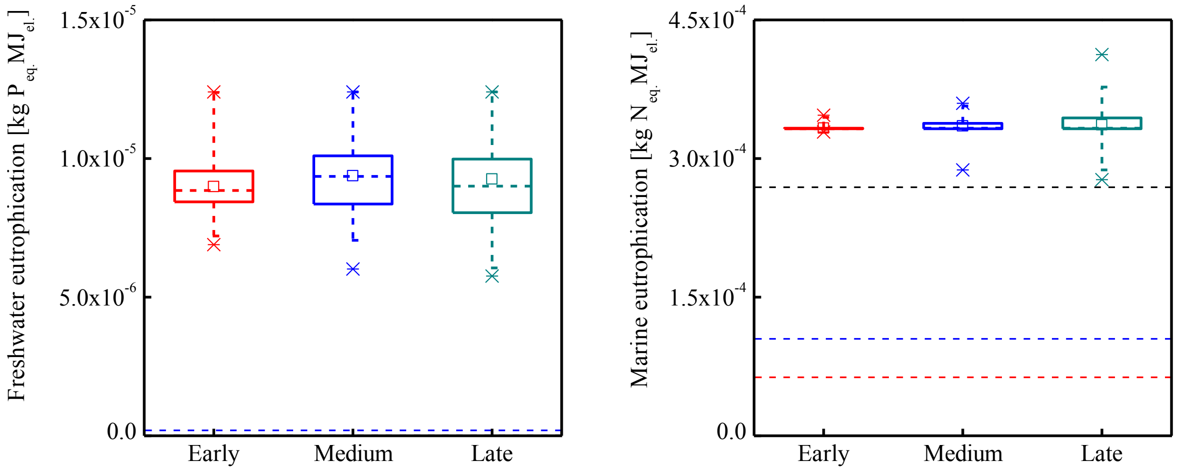


Fig. 4.2 - Boxplot graphs for all the impacts analysed in the base case. For each plot, the results for the three genotypes are depicted in different colours. The statistical distribution is based on the results obtained from the CropSyst model for the years 1976 – 2014. Each box illustrates maximum and minimum values (cross symbols), average (square symbol), 5% - 25% - 50% - 75% - 95% percentiles. For each plot dashed lines of different colours represent the environmental impact associated with the production of 1 MJ electricity using fossil sources: Natural Gas = Blue; Italian Electricity generation mix = Red; Hard coal = black; EU FFC (for GHG only)= Green.

Transport processes, composed by sorghum and straw transport, contribute in average for 2% of the total GHG emissions.

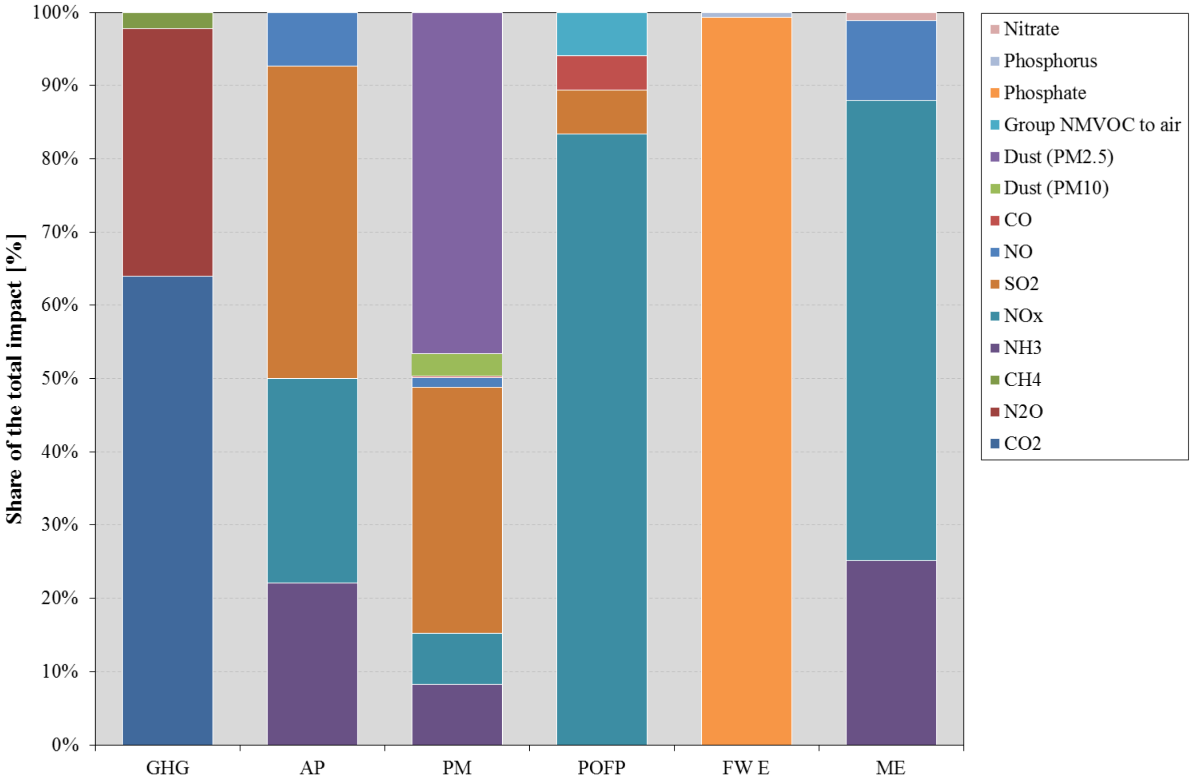


Fig. 4.3 - Contributional analysis by pollutant species, for all the environmental impacts assessed in their median year, in their base case.

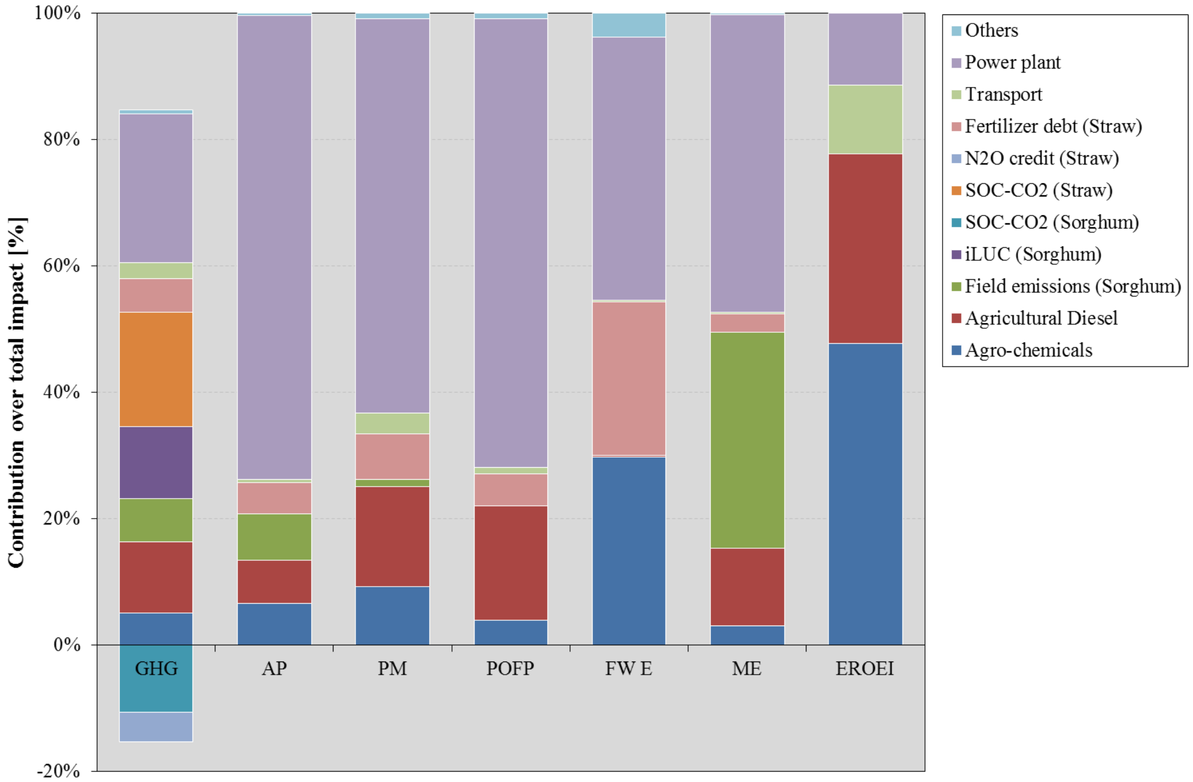


Fig. 4.4 - Contributional analysis by productive process for all the environmental impacts assessed in their median year in their base case.

A deeper decomposition of the GHG emission sources is shown in Fig. 4.5. The overall GHG emissions have a generally linear trend with the net yield of sorghum (net of losses and haymaking failures). While straw emissions are linear by design, emissions associated to sorghum production have a non-linearity factor due to the mechanical and respiration losses, and associated SOC accumulation, which are instead driven by the climate in the specific year considered. This causes the emissions to actually show a maximum value which is not necessarily linked to a failed harvest of sorghum. In fact, in the years with a total loss of the harvest of sorghum (net yield = 0) show total GHG emissions lower than for the years with a net yield of up to 15-16 Mg DM ha^{-1}. This shows that in years with low yield of sorghum and in situations with a sufficient supply of wheat straw, it may be even more beneficial to climate change mitigation to dedicate the harvest of sorghum or a fraction of it for soil amendment purposes albeit this carbon storage is usually not valued monetarily. However, further research should be conducted to evaluate better the dynamics of SOC accumulation under sorghum cultivation.

4.3.3 Acidification potential (AP)

The acidification potential, AP is expressed in moles of $H^+_{eq.}MJ^{-1}_{el}$ of entire biomass supply chain system and is calculated according to the accumulated exceedance method (Seppälä *et al.*, 2006, Posch *et al.*, 2008).

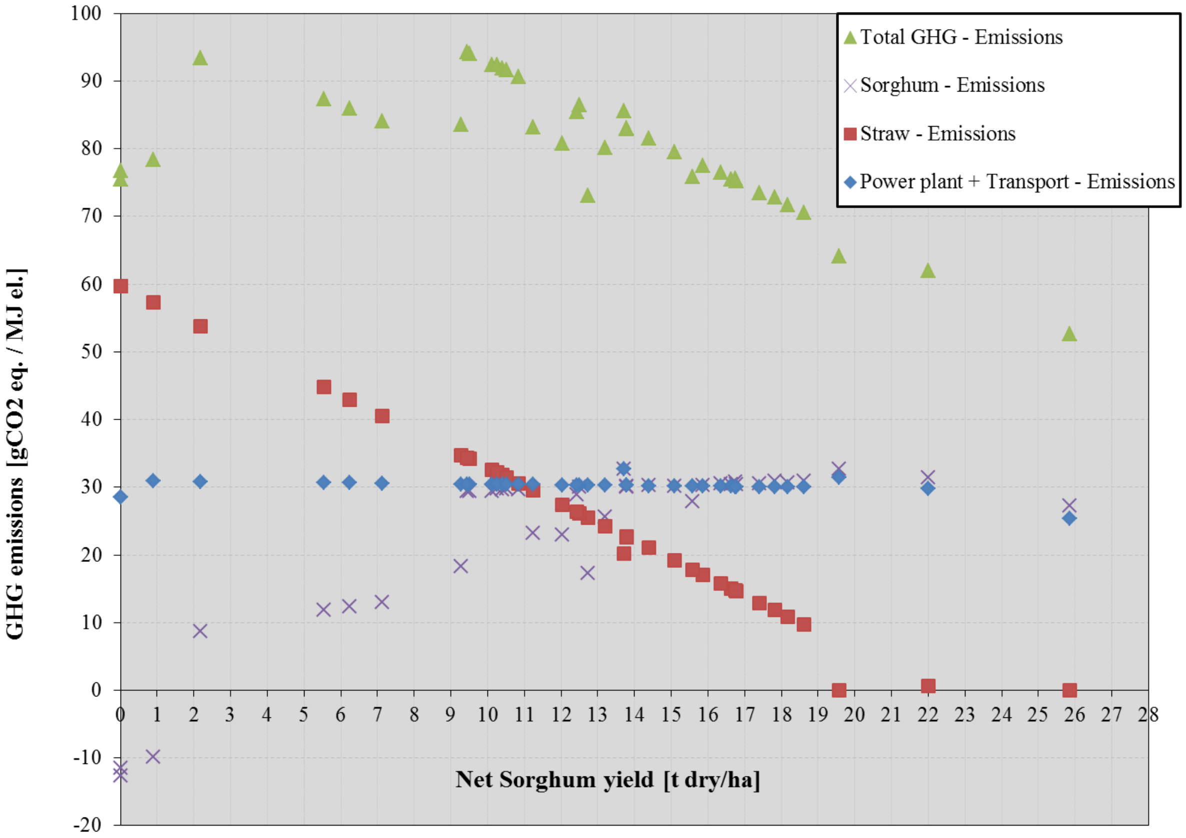


Fig. 4.5 - Medium-late genotype, disaggregation of GHG emissions by sorghum, straw and common processes, plotted in function of the net dry yield of sorghum.

The average AP emissions value of early sorghum genotype was calculated to be 9.21E^{-04} H$^{+}_{eq.}$MJ$^{-1}_{el.}$ and ranged from 8.83E^{-04} to 9.98E^{-04} H$^{+}_{eq.}$MJ$^{-1}_{el.}$. The average AP emissions value of medium-late genotype was calculated to be 9.33E^{-04} H$^{+}_{eq.}$MJ$^{-1}_{el.}$ and ranged from 7.72E^{-04} to 9.98E^{-04} H$^{+}_{eq.}$MJ$^{-1}_{el.}$. The average AP emissions value of late genotype was calculated to be 9.34E $^{-04}$ H$^{+}_{eq.}$MJ$^{-1}_{el.}$ and ranged from 7.42E^{-04} to 1.11E^{-04} H$^{+}_{eq.}$MJ$^{-1}_{el.}$. Considering all sorghum genotypes, in average, the main contributor to the AP emissions is represented by sulphur dioxide (43%) followed by nitrogen oxides (35%) and ammonia (22%) (Fig. 4.3). In terms of processes, end-use combustion in the power plant (73%) is the process that more contributes to AP emissions followed by overall emissions from sorghum cultivation (21%) (Fig. 4.4). In average, all three genotypes have a potential impact which is significantly higher than natural gas systems and then the current Italian power generation mix. In the years with low yields, all genotypes are even very close or higher than systems based on hard coal.

In the case considered here, the production of NH_3 from the DeNOx reaction strongly mitigates the benefits of the SNCR equipment; in fact considering a system without DeNO$_x$, the overall AP impact only increases by about 10 – 13%, as shown in Fig.4.6.

4.3.4 Freshwater and marine eutrophication (FWE and ME)

The impact on eutrophication is divided into two categories depending on the main substances responsible. In freshwater ecosystems phosphorus is the limiting element, therefore only P-compound (phosphorus and phosphate) emissions are analyzed for the assessment in freshwater eutrophication and impact are expressed in terms of kg $P_{eq.}$. In sea water the limiting factor for plant grown is N, hence the recommended method includes only N-compound (IES, 2012). The contributing substance are nitrate, ammonia and nitrogen oxides are take in consideration and expressed in terms of kg $N_{eq.}$ (IES, 2012). Both categories impact are calculated in according to the method ReCiPe (Goedkoop *et al.*, 2008).

The average freshwater eutrophication emissions value of early sorghum genotype was calculated to be $8.98E^{-06}$ kg $P_{eq.}MJ^{-1}{}_{el.}$ and it ranges from $6.84E^{-06}$ to $1.24E^{-05}$ kg $P_{eq.}MJ^{-1}{}_{el.}$. The average freshwater eutrophication emissions value of medium-late sorghum genotype was calculated to be $9.38E^{-06}$ kg $P_{eq.}MJ^{-1}{}_{el.}$ and it ranges from $6.01E^{-06}$ to $1.24E^{-05}$ kg $P_{eq.}MJ^{-1}{}_{el.}$. The average freshwater eutrophication emissions value of medium-late sorghum genotype was calculated to be $9.26E^{-06}$ kg $P_{eq.}MJ^{-1}{}_{el.}$ and it ranges from $5.77E^{-06}$ to $1.24E^{-05}$ kg $P_{eq.}MJ^{-1}{}_{el.}$.

The impact is almost completely caused by phosphates (99%) followed by phosphorus (1%) as reported in Fig. 4.3. The main contributing process is the ash disposal within the power plant (42%), followed by agro-chemicals use in sorghum cultivation (30%), and to complement nutrients removed with the straw (24%) as reported in Fig. 4.4.

Average FWE impact for this bioenergy system was higher value compared to the current power generation mix natural gas and hard coal pathway (Fig. 4.2).

The average marine eutrophication emissions value of early sorghum genotype was calculated to be $3.33E^{-04}$ kg $N_{eq}.MJ^{-1}{}_{el.}$ and it ranged from $3.30E^{-04}$ to $3.47E^{-04}$ kg $N_{eq.}MJ^{-1}{}_{el.}$. The average marine eutrophication emissions value of medium-late sorghum genotype was calculated to be $3.35E^{-04}$ kg $N_{eq.}MJ^{-1}{}_{el.}$ and it ranged from $2.88E^{-04}$ to $3.60E^{-04}$ kg $N_{eq.}MJ^{-1}{}_{el.}$. The average marine eutrophication emissions value of late sorghum genotype was calculated to be $3.36E^{-04}$ kg $N_{eq.}MJ^{-1}{}_{el.}$ and it ranged from $2.77E^{-04}$ to $4.13E^{-04}$ kg $N_{eq.}MJ^{-1}{}_{el.}$. The main pollutants contributing to the marine eutrophication impact are nitrogen oxides (74%) followed by ammonia (25%) and nitrates (1%) (Fig. 4.3). The main process contributing to this impact are is sorghum cultivation (49%) followed by combustion emissions from the power plant (47%) (Fig.4.4). Average ME impact for this bioenergy system was lower compared to the current power generation mix natural gas and hard coal pathway (Fig. 4.2).

4.3.5 Particulate Matter/Respiratory inorganic (PM/RI)

Particulate matter emissions are expressed in terms of kg PM2.5$_{eq.}$ and are evaluated with the RiskPoll software (Rabl and Spadaro, 2004, Greco *et al.*, 2007).

The average PM emissions value of early sorghum genotype was calculated to be 5.40E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 4.79E^{-05} to 6.39E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$. The average PM emissions value of medium-late sorghum genotype was calculated to be 5.54E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 4.17E^{-05} to 6.52E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$. The average PM emissions value of late sorghum genotype was calculated to be 5.51E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 4.01E^{-05} to 6.48E^{-05} kg PM2.5$_{eq.}$MJ^{-1}$_{el.}$.

The main contributor to the PM emissions is represented by direct particulate emissions, mainly PM 2.5 (50%), followed by sulphur dioxide (34%), ammonia (8%) and nitrogen oxides (7%) (Fig. 3). In terms of processes, the power plant (62%) is the process that contributes most to PM emissions followed by sorghum cultivation (26%) (Fig. 4.4).

Average PM impact for this bioenergy system is similar to a hard coal pathway, with much higher values compared to the current power generation mix.

4.3.7 Photochemical ozone formation potential (POFP)

The photochemical ozone formation potential is expressed in terms of kg NMVOC$_{eq.}$ and is calculated according to the method ReCiPe (Goedkoop *et al.*, 2008).

The average POFP emissions value of early sorghum genotype was calculated to be 4.19E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 4.11E^{-04} to 4.44E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$. The average POFP emissions value of medium-late sorghum genotype was calculated to be 4.23E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 3.6E^{-04} to 4.54E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$. The average POFP emissions value of late sorghum genotype was calculated to be 4.24E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$ and it ranged from 3.47E^{-04} to 5.07E^{-04} kg NMVOC$_{eq.}$MJ^{-1}$_{el.}$.

Considering all sorghum genotypes, in average, the main contributor to the POFP emissions is represented by nitrogen oxides (83%) followed by sulphur dioxide (6%), NMVOCs (6%) and carbon monoxide (5%) (Fig. 4.3). In terms of processes, the power plant (71%) is the process that contributes the most to POFP impact, followed by sorghum cultivation (22%) (Fig. 4.4).

4.3.9 Energy return on Energy investment (EROEI)

The Energy Return on Energy Investment index (EROEI) presents a positive value for the three sorghum genotypes considered (Fig. 4.5). In details, early genotype shows an average EROEI of 2.59, ranging from 1.83 in the year with the lowest sorghum yield (1982) to 3.39 in the year with the highest yield (1989). The medium-late genotype and the late genotype show an average EROEI of 2.49 and 2.56, respectively. EROEI is affected by the biomass sorghum production. Early genotype shows the highest EROEI (average 2.59) linked to the highest baled biomass (14.04 Mg DM $ha^{-1}y^{-1}$) (Chapter 3). The main processes utilizing non-renewable energy are linked to the cultivation of biomass sorghum (78%), with an 11% contribution each due to transport of the materials and power plant construction (Fig. 4.4).

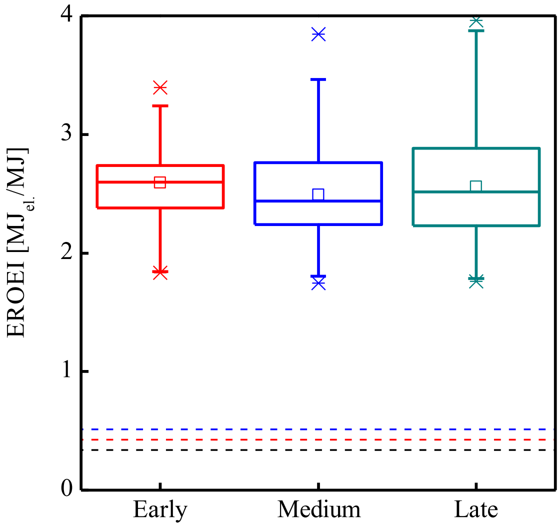


Fig. 4.5 - Boxplot graph for the EROEI category in the base case. The results for the three genotypes are depicted in different colours. The statistical distribution is based on the results obtained from the CropSyst model for the years 1976 – 2014. Each box illustrates maximum and minimum values (cross symbols), average (square symbol), 5% - 25% - 50% - 75% - 95% percentiles. Dashed lines of different colours represent the environmental impact associated with the production of 1 MJ electricity using fossil sources: Natural Gas = Blue; Italian Electricity generation mix = Red; Hard coal = black.

4.3.10 Sensitivity analysis

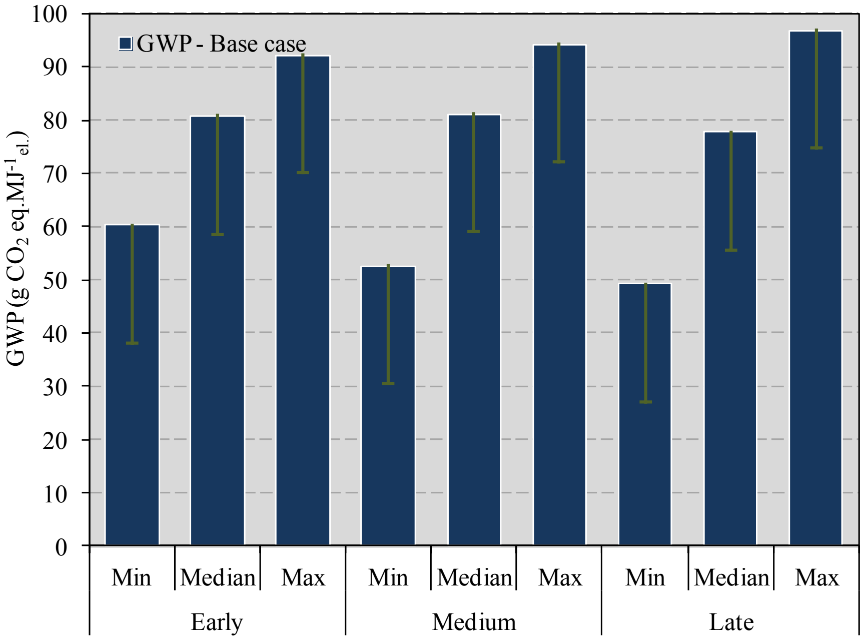
As mentioned above, we have carried out several additional calculations to test the impact of the most important assumptions defined in the base case.

4.3.11 DeNOx SNCR impact

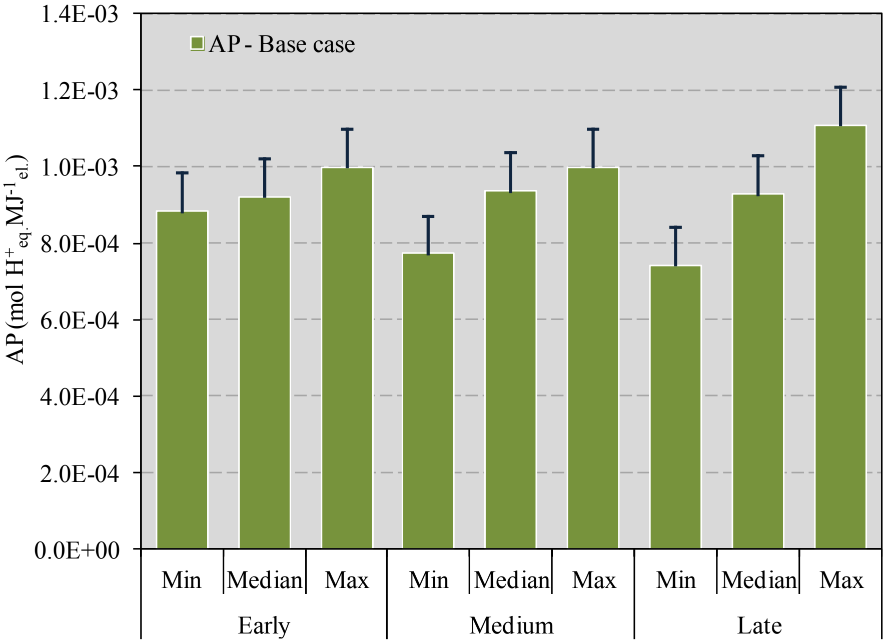
Fig. 4.6 presents all the impacts in the case in which the power plant is not equipped with a DeNO$_x$ SNCR. It is clear that the SNCR achieves in large part its purpose by lowering all impacts. However, as it is evident especially for the particulate matter (PM) category, the reduction in NO$_x$ emissions is perfectly balanced, in our model, by the increased emissions of NH_3 so that no net change is recorded.

Another important burden shift may be with the GHG emissions. In fact, N_2O is a potential product of the DeNO$_x$ reaction taking place in SNCR reactors. In our model, thus, a flue gas cleaning technology to decrease local pollutants causes an increase between 23% and 45% in the climate change impact of the whole system (Fig. 4.6a).

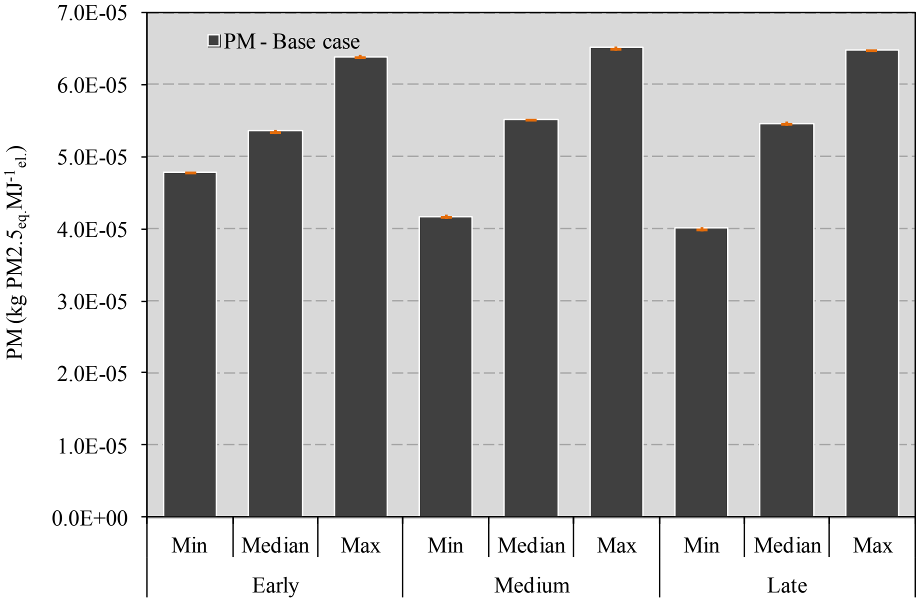
(a)


GWP - Base case
GWP (g CO2 eq.MJ-1 el.)
100
90
80
70
60
50
40
30
20
10
0
Min
Median
Max
Min
Median
Max
Min
Median
Max
Early
Medium
Late

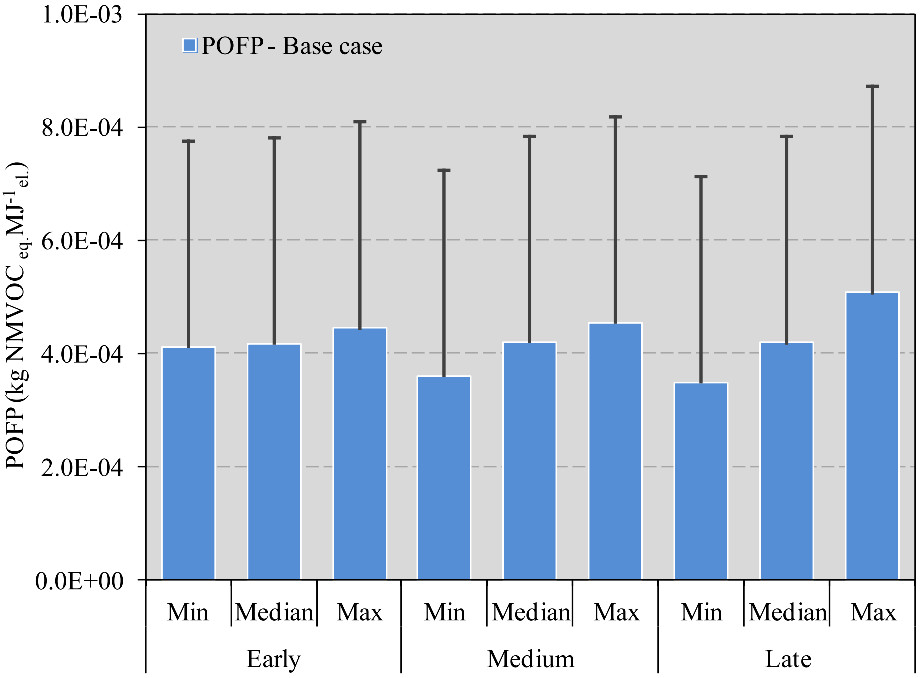
(b)


AP - Base case
AP (mol H+ eq. MJ-1 el.)
1.4E-03
1.2E-03
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
Min
Median
Max
Min
Median
Max
Min
Median
Max
Early
Medium
Late

(c)


PM - Base case
PM (kg PM2.5eq.MJ-1el.)
7.0E-05
6.0E-05
5.0E-05
4.0E-05
3.0E-05
2.0E-05
1.0E-05
0.0E+00
Min
Median
Max
Min
Median
Max
Min
Median
Max
Early
Medium
Late

(d)


POFP - Base case
POFP (kg NMVOC eq.MJ-1el.)
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
Min
Median
Max
Min
Median
Max
Min
Median
Max
Early
Medium
Late

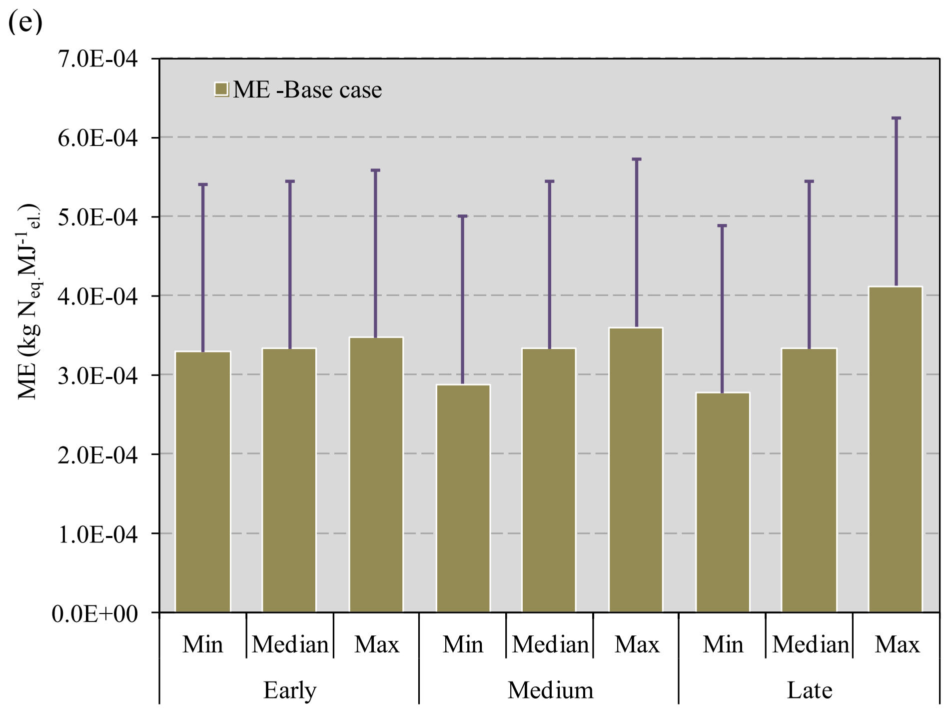


Fig. 4.6 - Results from the sensitivity analysis when no DeNO$_x$ system is installed in the power plant. All impacts affected are reported for the three genotypes considered; only the years with the minimum, maximum and median values are analysed. The columns represent the value in the base case (also depicted in Fig. 4.2) while the error bars indicate the value without SNCR equipment.

4.3.12 iLUC emission factor

Fig. 4.7a illustrates the change in GHG emissions for the three genotypes when the iLUC emission factor is not included. The average GHG emissions decrease by approximately of the 16%, making the emissions from the bioenergy system about 52% lower than the emissions from a natural gas plant.

4.3.13 SOC emission factor

Fig. 4.7b,c show the results of the influence of using higher or lower SOC emission factors for straw removal and sorghum incorporation.

Specifically, Fig. 4.7c, illustrates the results obtained by increasing or decreasing by 25% the SOC emission factor for both straw and sorghum. This change only changes the average GHG emissions by about 3%. This is not a negligible influence but it also indicates that a different value for this parameter would not invalidate or significantly change the conclusions of this study. Nonetheless, further investigation, both experimental and numerical, into the soil dynamics involved would be beneficial for a better understanding of the dynamic climate impacts of the bioenergy system.

Finally, Fig. 4.7b shows the results obtained when modifying the value of the SOC emission factor for Sorghum as compared to the value used for straw. In this case a relative increase of the SOC factor for sorghum indicates a lower liability of the carbon content in sorghum while a decrease indicates faster decomposition in the soil. The differences also in this case are limited and this assumption does not influence the main results of this study.

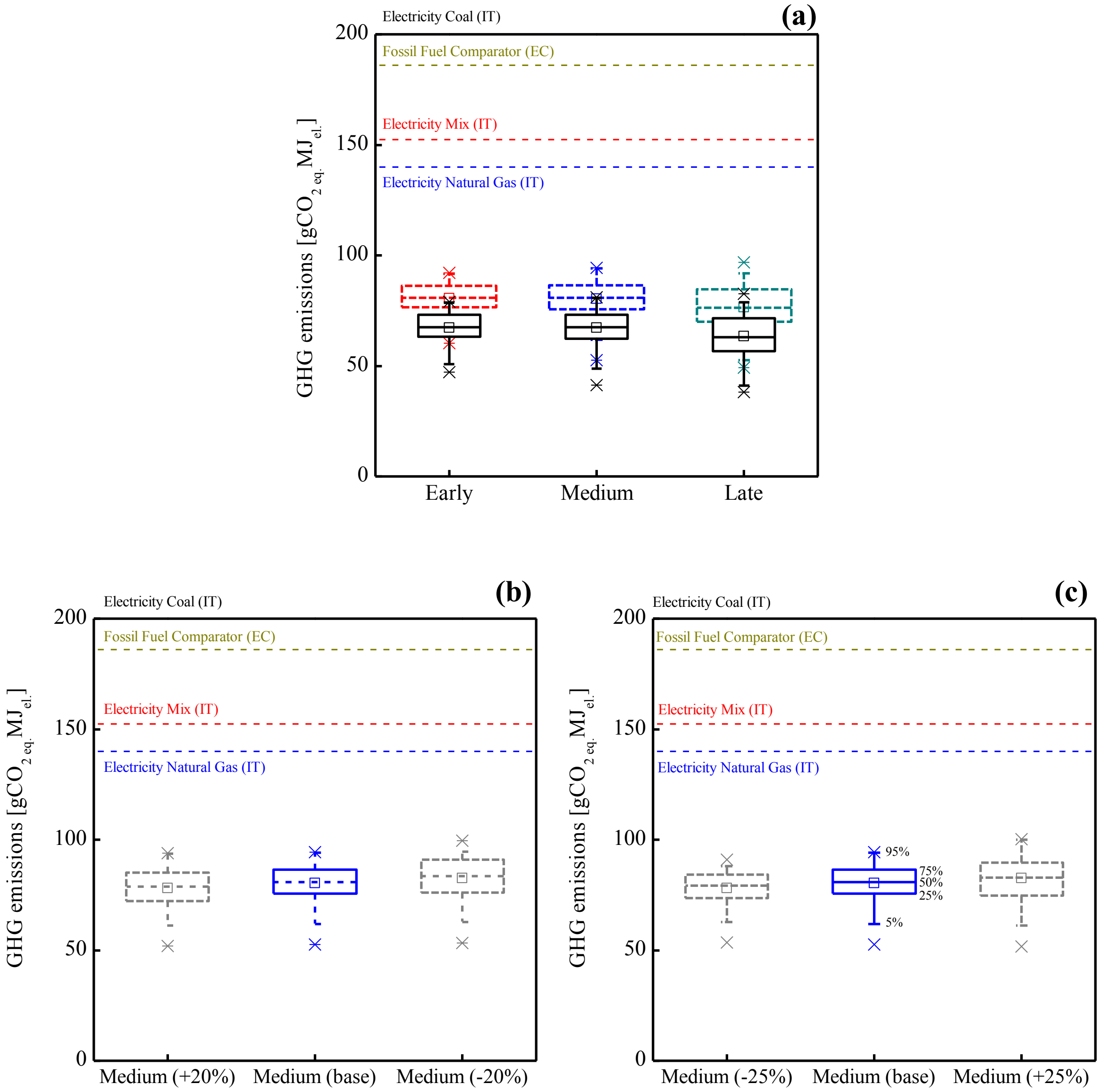


Fig. 4.7 - Sensitivity analysis for GHG emissions impact. a) GHG emissions for the three genotypes excluding iLUC emission factor. Results for the base case are also shown in dashed border. b) Sensitivity of overall GHG emissions for the medium genotype to an change of parameter for CO_2 emissions due to SOC change; the change indicated is relative between the emission factor considered for straw and for sorghum. c) Sensitivity of overall GHG emissions for the medium genotype to an overall change of parameter for CO_2 emissions due to SOC change for straw removal (and CO_2 credits for sorghum incorporation in soil).

4.4 Conclusions

In this study the environmental impacts, from cradle to grave, and energy performance of three sorghum genotypes to generate electricity by direct combustion in a power plant were quantified. Late sorghum genotype shows the lowest average GHG emissions (76.58 g $CO_{2eq.}MJ^{-1}{}_{el.}$) while medium-late and early genotypes show similar emission values of 80.52 g $CO_{2eq.}MJ^{-1}_{el.}$ and 80.43 g $CO_{2eq.}MJ^{-1}_{el.,}$ respectively. All values are lower than reference fossil systems considered.

In all impact categories the power plant is the process contributing most to the environmental emissions. The application of $DeNO_x$ SNCR may cause a trade-off between an increase, between 23% and 45%, in the climate change impact while mitigating all other impacts, especially Acidification potential and photochemical oxidant formation. The inclusion of carbon emissions due to iLUC contributes to about 10% of total GHG emissions. The climate change impact category results to have a small sensitivity to the changes in emissions/accumulation of SOC due to straw removal and sorghum incorporation.

The study shows the highest energy performance of the bioenergy system considered if it is compared to the conventional fossil sources.

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Annex 1

4.1 Soil organic carbon (SOC) and CO_2 emissions dynamics in the simulated period

4.1.1 Methodology to simulate soil organic carbon change (ΔSOC) and CO_2 emissions

In this work, the CO_2 emissions due straw removal were estimated followed these steps: (I) for each simulated years (39 years) and three soil types ("VIC1", "ISN1" and "CCO1") was calculated the soil organic carbon change (ΔSOC) as difference between SOC contents in the two simulated scenarios (soil straw incorporation – soil straw removal); (II) average ΔSOC was annualized using a time period of 20 years (assumed as lifespan of the biomass power plant) and (III) multiplied for the stoichiometry ratio between carbon dioxide and carbon.

A specific CO_2 emission factor associated to the wheat straw feedstock, equal to 0.15 kg CO_2 kg^{-1} dry straw, was calculated dividing the average value of the CO_2 emissions of three soils considered (736.46 kg CO_2 ha^{-1} y^{-1}) for the average of straw produce commonly in the target area (5 Mg DM ha^{-1} y^{-1}). This factor was placed in a specific process in Gabi and trough a simple algorithm, the CO_2 carbon emissions due to soil straw removal were made proportionally at the yearly amount of straw used to complement sorghum to cover biomass power plant.

4.1.2 Results

Fig. 4.1a shows the simulation results of soil organic carbon change (ΔSOC). ΔSOC content increases during simulated years in which winter wheat was cultivated (grey columns), due to straw incorporation. Soil "VIC1" presents the highest increase of SOC in the simulated period followed by soil "CCO1" and soil "ISN1". In details, soil "VIC1" presents a significantly ΔSOC increase (ANOVA *F:*14.71, *P<0.001*) of 5 Mg $ha^{-1}y^{-1}$ followed by soil "CCO1" (3.64 Mg $ha^{-1}y^{-1}$) and soil "ISN1" (3.41 Mg $ha^{-1}y^{-1}$) (Fig. 1b).

Fig. 4.2b shows the CO_2 emissions related to field straw removal. The CO_2 emissions are highest in soil "VIC1" followed by soil "CCO1" and soil "ISN1". The soil "VIC1" shows the highest CO_2 (ANOVA *F*: 14.71; *P*<0.001), 917.46 kg ha^{-1} y^{-1}, followed by soil "CCO1" (688.10 Mg ha^{-1} y^{-1}) and soil "SNI1" (624.60 Mg ha^{-1} y^{-1}).

The CO_2 emissions represents the missed carbon stock sequestration due to straw removal and are emitted in atmosphere during straw combustion in biomass power plant. It was interesting to note that in the years, in which wheat straw was removed, CO_2 emission presented the highest values (Fig. 4.1a) and that CO_2 emissions increase from soil SNI1 to VIC1 due to the increase of ΔSOC.

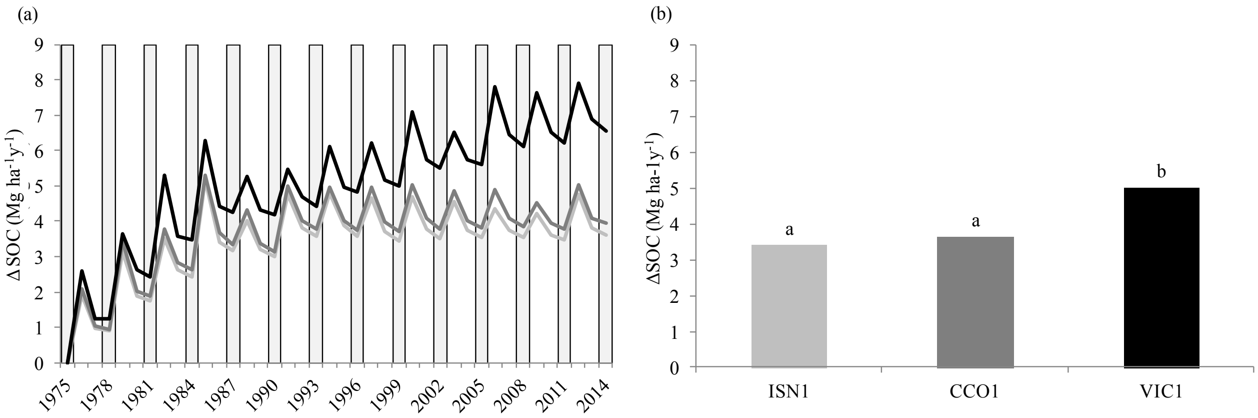

Fig. 4.1 - Results of simulated soil organic carbon change (ΔSOC). (a) ΔSOC dynamic in the simulated period for the three soils (black= VIC1, dark grey= CCO1 and light grey= ISN1). (b) Average SOC for the soils considered. Different letters showed statistical differences means (Tukey's HSD Test $p<0.05$).

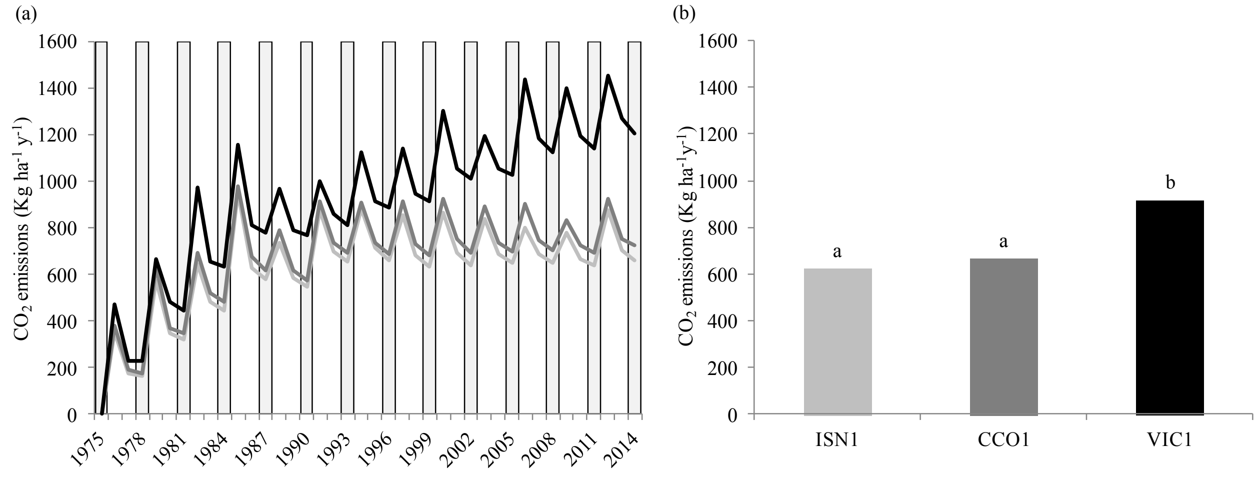

Fig. 4.2 - Results of simulated CO_2 emissions. (a) CO_2 dynamic in the simulated period for the three soils (black= VIC1, dark grey= CCO1 and light grey= ISN1). (b) Average CO_2 for the soils considered in this study. Different letters showed statistical differences means (Tukey's HSD Test $p<0.05$).

Table 4.1 - Summary of the numerical results for all environmental impacts assessed for all genotypes and for all the years simulated.

Simulated years	Sorghum genotype	GWP (gCO$_2$ $_{eq.}$MJ^{-1}$_{el.}$)	Acidification potentail (H$^{+}_{eq.}$MJ$^{-1}_{el.}$)	Freshwater Eutrophication (kg P$_{eq.}$ MJ$^{-1}_{el.}$)	Marine Eutrophication (kg N $_{eq.}$ MJ$^{-1}_{el.}$)	Particular Matter potential (kg PM2.5$_{eq.}$ MJ$^{-1}_{el.}$)	Photochemical Ozone Formation Potential (kg NMVOC$_{eq.}$ MJ$^{-1}_{el.}$)	EROEI (MJ MJ^{-1})
1976	early	86.28	9.30E-04	9.36E-06	3.33E-04	5.51E-05	4.18E-04	2.43
1977	early	64.05	8.98E-04	7.21E-06	3.33E-04	4.91E-05	4.16E-04	3.24
1978	early	63.92	8.98E-04	7.22E-06	3.33E-04	4.91E-05	4.16E-04	3.24
1979	early	79.53	9.20E-04	8.72E-06	3.32E-04	5.33E-05	4.17E-04	2.63
1980	early	78.35	9.18E-04	8.60E-06	3.32E-04	5.29E-05	4.17E-04	2.67
1981	early	83.99	9.90E-04	1.24E-05	3.45E-04	6.37E-05	4.43E-04	1.83
1982	early	82.10	9.24E-04	8.97E-06	3.32E-04	5.40E-05	4.17E-04	2.55
1983	early	83.38	9.26E-04	9.07E-06	3.32E-04	5.43E-05	4.18E-04	2.52
1984	early	85.67	9.28E-04	9.23E-06	3.32E-04	5.47E-05	4.18E-04	2.47
1985	early	76.48	9.15E-04	8.41E-06	3.32E-04	5.24E-05	4.16E-04	2.74
1986	early	72.89	9.11E-04	8.10E-06	3.32E-04	5.15E-05	4.16E-04	2.86
1987	early	79.33	9.22E-04	8.82E-06	3.33E-04	5.36E-05	4.18E-04	2.60
1988	early	60.34	8.83E-04	6.89E-06	3.29E-04	4.78E-05	4.11E-04	3.40
1989	early	87.54	9.98E-04	1.24E-05	3.47E-04	6.39E-05	4.44E-04	1.84
1990	early	80.75	9.22E-04	8.84E-06	3.32E-04	5.36E-05	4.17E-04	2.60
1991	early	90.85	9.37E-04	9.79E-06	3.33E-04	5.63E-05	4.19E-04	2.32
1992	early	68.47	9.05E-04	7.68E-06	3.32E-04	5.03E-05	4.16E-04	3.03
1993	early	78.09	9.18E-04	8.60E-06	3.32E-04	5.29E-05	4.16E-04	2.68
1994	early	70.60	9.08E-04	7.88E-06	3.32E-04	5.09E-05	4.16E-04	2.95
1995	early	80.32	9.21E-04	8.77E-06	3.32E-04	5.34E-05	4.17E-04	2.62
1996	early	89.74	9.35E-04	9.67E-06	3.33E-04	5.60E-05	4.19E-04	2.35
1997	early	74.49	9.13E-04	8.24E-06	3.32E-04	5.19E-05	4.16E-04	2.80
1998	early	76.37	9.15E-04	8.43E-06	3.32E-04	5.24E-05	4.16E-04	2.74
1999	early	83.43	9.36E-04	9.58E-06	3.34E-04	5.60E-05	4.22E-04	2.36
2000	early	78.15	9.18E-04	8.60E-06	3.32E-04	5.29E-05	4.17E-04	2.68
2001	early	86.26	9.30E-04	9.34E-06	3.32E-04	5.50E-05	4.18E-04	2.44
2002	early	86.26	9.30E-04	9.34E-06	3.32E-04	5.50E-05	4.18E-04	2.44

2003	early	91.64	9.38E-04	9.87E-06	3.33E-04	5.65E-05	4.19E-04	2.30
2004	early	91.73	9.38E-04	9.85E-06	3.33E-04	5.65E-05	4.19E-04	2.30
2005	early	88.37	9.33E-04	9.55E-06	3.33E-04	5.56E-05	4.18E-04	2.38
2006	early	92.15	9.39E-04	9.91E-06	3.33E-04	5.67E-05	4.19E-04	2.29
2007	early	82.12	9.24E-04	8.97E-06	3.32E-04	5.40E-05	4.17E-04	2.55
2008	early	76.81	9.16E-04	8.44E-06	3.32E-04	5.25E-05	4.17E-04	2.73
2009	early	90.48	9.36E-04	9.74E-06	3.33E-04	5.62E-05	4.19E-04	2.33
2010	early	81.14	9.22E-04	8.86E-06	3.32E-04	5.37E-05	4.17E-04	2.59
2011	early	74.98	9.14E-04	8.30E-06	3.32E-04	5.21E-05	4.16E-04	2.78
2012	early	86.33	9.30E-04	9.37E-06	3.32E-04	5.51E-05	4.18E-04	2.43
2013	early	79.24	9.20E-04	8.71E-06	3.32E-04	5.32E-05	4.17E-04	2.64
2014	early	77.73	9.18E-04	8.55E-06	3.32E-04	5.28E-05	4.17E-04	2.69
1976	medium-late	85.97	9.62E-04	1.09E-05	3.39E-04	6.02E-05	4.32E-04	2.02
1977	medium-late	75.52	9.98E-04	1.24E-05	3.51E-04	6.45E-05	4.54E-04	1.80
1978	medium-late	78.35	9.95E-04	1.22E-05	3.49E-04	6.51E-05	4.53E-04	1.75
1979	medium-late	84.04	9.58E-04	1.07E-05	3.39E-04	5.96E-05	4.32E-04	2.07
1980	medium-late	80.12	9.30E-04	9.19E-06	3.34E-04	5.48E-05	4.21E-04	2.47
1981	medium-late	76.72	9.96E-04	1.24E-05	3.50E-04	6.43E-05	4.51E-04	1.81
1982	medium-late	75.53	9.15E-04	8.35E-06	3.32E-04	5.22E-05	4.16E-04	2.76
1983	medium-late	83.08	9.25E-04	9.05E-06	3.32E-04	5.42E-05	4.17E-04	2.53
1984	medium-late	93.39	9.79E-04	1.19E-05	3.41E-04	6.32E-05	4.37E-04	1.84
1985	medium-late	72.84	9.10E-04	8.06E-06	3.32E-04	5.14E-05	4.16E-04	2.87
1986	medium-late	71.64	9.09E-04	7.98E-06	3.32E-04	5.12E-05	4.16E-04	2.90
1987	medium-late	79.47	9.20E-04	8.73E-06	3.32E-04	5.33E-05	4.17E-04	2.63
1988	medium-late	52.59	7.72E-04	6.01E-06	2.88E-04	4.17E-05	3.60E-04	3.85
1989	medium-late	64.07	9.53E-04	7.54E-06	3.57E-04	5.14E-05	4.39E-04	3.46
1990	medium-late	85.57	9.97E-04	9.42E-06	3.60E-04	5.76E-05	4.51E-04	2.46
1991	medium-late	94.06	9.42E-04	1.01E-05	3.33E-04	5.72E-05	4.20E-04	2.24
1992	medium-late	61.91	8.96E-04	7.05E-06	3.33E-04	4.86E-05	4.16E-04	3.32
1993	medium-late	83.54	9.48E-04	1.01E-05	3.37E-04	5.78E-05	4.27E-04	2.20
1994	medium-late	73.04	9.37E-04	9.30E-06	3.38E-04	5.56E-05	4.28E-04	2.40
1995	medium-late	87.36	9.65E-04	1.11E-05	3.39E-04	6.07E-05	4.33E-04	1.99

1996	medium-late	91.86	9.38E-04	9.87E-06	3.33E-04	5.66E-05	4.20E-04	2.29
1997	medium-late	70.57	9.08E-04	7.87E-06	3.32E-04	5.09E-05	4.16E-04	2.95
1998	medium-late	77.52	9.17E-04	8.54E-06	3.32E-04	5.27E-05	4.17E-04	2.70
1999	medium-late	83.11	9.38E-04	9.66E-06	3.35E-04	5.62E-05	4.23E-04	2.33
2000	medium-late	75.18	9.14E-04	8.32E-06	3.32E-04	5.21E-05	4.16E-04	2.78
2001	medium-late	86.42	9.30E-04	9.36E-06	3.32E-04	5.51E-05	4.18E-04	2.44
2002	medium-late	81.58	9.23E-04	8.90E-06	3.32E-04	5.38E-05	4.17E-04	2.57
2003	medium-late	92.39	9.39E-04	9.94E-06	3.33E-04	5.67E-05	4.19E-04	2.28
2004	medium-late	92.33	9.39E-04	9.91E-06	3.33E-04	5.67E-05	4.19E-04	2.29
2005	medium-late	90.62	9.37E-04	9.76E-06	3.33E-04	5.63E-05	4.19E-04	2.32
2006	medium-late	94.25	9.42E-04	1.01E-05	3.33E-04	5.72E-05	4.20E-04	2.24
2007	medium-late	82.92	9.25E-04	9.04E-06	3.32E-04	5.42E-05	4.18E-04	2.53
2008	medium-late	75.56	9.14E-04	8.32E-06	3.32E-04	5.21E-05	4.16E-04	2.77
2009	medium-late	91.60	9.38E-04	9.84E-06	3.33E-04	5.65E-05	4.19E-04	2.30
2010	medium-late	76.43	9.16E-04	8.42E-06	3.32E-04	5.24E-05	4.16E-04	2.74
2011	medium-late	73.49	9.11E-04	8.16E-06	3.32E-04	5.17E-05	4.16E-04	2.84
2012	medium-late	85.50	9.31E-04	9.38E-06	3.33E-04	5.52E-05	4.19E-04	2.43
2013	medium-late	80.71	9.35E-04	9.47E-06	3.35E-04	5.57E-05	4.23E-04	2.38
2014	medium-late	75.91	9.20E-04	8.61E-06	3.33E-04	5.30E-05	4.18E-04	2.66
1976	late	85.95	9.89E-04	1.24E-05	3.44E-04	6.36E-05	4.41E-04	1.84
1977	late	54.67	7.96E-04	6.20E-06	2.96E-04	4.30E-05	3.71E-04	3.74
1978	late	68.53	1.04E-03	9.82E-06	3.77E-04	6.05E-05	4.78E-04	2.28
1979	late	80.95	9.92E-04	1.24E-05	3.47E-04	6.40E-05	4.46E-04	1.82
1980	late	73.09	9.11E-04	8.10E-06	3.32E-04	5.15E-05	4.17E-04	2.85
1981	late	72.30	1.00E-03	1.24E-05	3.53E-04	6.48E-05	4.58E-04	1.79
1982	late	80.78	9.89E-04	1.20E-05	3.47E-04	6.43E-05	4.48E-04	1.79
1983	late	77.81	9.18E-04	8.55E-06	3.32E-04	5.28E-05	4.17E-04	2.69
1984	late	87.69	9.90E-04	1.22E-05	3.45E-04	6.47E-05	4.45E-04	1.76
1985	late	69.01	9.05E-04	7.70E-06	3.32E-04	5.04E-05	4.16E-04	3.02
1986	late	67.27	9.03E-04	7.57E-06	3.32E-04	5.00E-05	4.15E-04	3.08
1987	late	78.52	9.21E-04	8.74E-06	3.33E-04	5.34E-05	4.18E-04	2.62
1988	late	49.17	7.42E-04	5.77E-06	2.77E-04	4.01E-05	3.48E-04	3.96

1989	late	52.62	7.74E-04	6.05E-06	2.88E-04	4.17E-05	3.59E-04	3.88
1990	late	73.94	1.11E-03	8.79E-06	4.12E-04	5.97E-05	5.07E-04	2.75
1991	late	96.83	1.02E-03	1.11E-05	3.61E-04	6.24E-05	4.57E-04	2.03
1992	late	70.72	9.75E-04	1.10E-05	3.48E-04	6.15E-05	4.49E-04	1.95
1993	late	79.91	9.45E-04	9.91E-06	3.37E-04	5.72E-05	4.28E-04	2.25
1994	late	81.21	9.92E-04	1.24E-05	3.46E-04	6.40E-05	4.46E-04	1.82
1995	late	71.90	9.14E-04	8.22E-06	3.33E-04	5.20E-05	4.19E-04	2.79
1996	late	88.82	9.42E-04	9.99E-06	3.34E-04	5.71E-05	4.22E-04	2.25
1997	late	67.07	9.03E-04	7.53E-06	3.32E-04	5.00E-05	4.16E-04	3.09
1998	late	82.76	9.58E-04	1.06E-05	3.39E-04	5.94E-05	4.32E-04	2.08
1999	late	76.31	9.28E-04	9.01E-06	3.35E-04	5.44E-05	4.22E-04	2.51
2000	late	69.82	9.07E-04	7.81E-06	3.32E-04	5.07E-05	4.16E-04	2.97
2001	late	84.68	9.28E-04	9.19E-06	3.32E-04	5.46E-05	4.18E-04	2.48
2002	late	73.21	9.11E-04	8.11E-06	3.32E-04	5.15E-05	4.16E-04	2.85
2003	late	90.34	9.36E-04	9.75E-06	3.33E-04	5.62E-05	4.19E-04	2.33
2004	late	90.61	9.36E-04	9.74E-06	3.33E-04	5.62E-05	4.19E-04	2.33
2005	late	87.16	9.31E-04	9.44E-06	3.32E-04	5.53E-05	4.18E-04	2.41
2006	late	91.98	9.38E-04	9.89E-06	3.33E-04	5.66E-05	4.19E-04	2.29
2007	late	78.82	9.19E-04	8.66E-06	3.32E-04	5.31E-05	4.17E-04	2.65
2008	late	69.31	9.05E-04	7.78E-06	3.31E-04	5.05E-05	4.14E-04	3.00
2009	late	89.87	9.35E-04	9.68E-06	3.33E-04	5.60E-05	4.19E-04	2.35
2010	late	69.99	9.07E-04	7.81E-06	3.32E-04	5.07E-05	4.16E-04	2.97
2011	late	72.22	9.10E-04	8.04E-06	3.32E-04	5.13E-05	4.16E-04	2.88
2012	late	80.78	9.22E-04	8.85E-06	3.32E-04	5.36E-05	4.17E-04	2.59
2013	late	74.51	9.13E-04	8.26E-06	3.32E-04	5.20E-05	4.17E-04	2.80
2014	late	75.58	9.48E-04	9.92E-06	3.39E-04	5.75E-05	4.32E-04	2.23

Table 4.2 - Summary of the production yields and losses obtained from CropSyst simulation for all genotypes for each year simulated.

Simulated years	Sorghum genotype	Sorghum total production (Mg DM)	Sorghum losses (Mg DM)	Haymaking failure (Mg DM)	Sorghum baled production (Mg DM)	Sorghum baled production (Mg DM ha^{-1})	Sorghum surplus (Mg DM ha^{-1})	Straw (Mg DM ha^{-1})
1976	early	64442.68	11791.79	0	52650.89	12.47	0	41349.11
1977	early	110310.33	20375.61	0	89934.72	21.30	0	4065.28
1978	early	110147.98	20269.92	0	89878.06	21.29	0	4121.94
1979	early	78003.29	14269.34	0	63733.95	15.10	0	30266.05
1980	early	80697.07	14853.53	0	65843.54	15.60	0	28156.46
1981	early	100835.24	0	100835.24	0	0	0	94000
1982	early	72448.58	12975.19	0	59473.40	14.09	0	34526.60
1983	early	70771.25	13064.33	0	57706.92	13.67	0	36293.08
1984	early	66735.05	11795.50	0	54939.55	13.01	0	39060.45
1985	early	84915.67	15643.87	0	69271.80	16.41	0	24728.20
1986	early	91534.08	16921.65	0	74612.43	17.67	0	19387.57
1987	early	79431.28	14092.93	3177.25	62161.10	14.72	0	31838.90
1988	early	116701.92	21581.30	0	95120.63	22.53	1120.63	0
1989	early	89033.51	0	89033.51	0	0	0	94000
1990	early	73147.29	11470.99	0	61676.30	14.61	0	32323.70
1991	early	52613.94	7395.87	0	45218.07	10.71	0	48781.93
1992	early	100515.50	18593.84	0	81921.66	19.41	0	12078.34
1993	early	79239.71	13304.42	0	65935.29	15.62	0	28064.71
1994	early	95571.37	17141.82	0	78429.55	18.58	0	15570.45
1995	early	77254.48	14276.27	0	62978.21	14.92	0	31021.79
1996	early	57708.90	10394.63	0	47314.27	11.21	0	46685.73
1997	early	88486.30	16326.49	0	72159.81	17.09	0	21840.19
1998	early	82021.96	13263.56	0	68758.40	16.29	0	25241.60
1999	early	74794.40	10962.98	14958.88	48872.53	11.58	0	45127.47
2000	early	80082.21	14117.05	0	65965.16	15.63	0	28034.84
2001	early	63878.48	10841.22	0	53037.26	12.56	0	40962.74
2002	early	64195.61	11090.42	0	53105.19	12.58	0	40894.81
2003	early	50724.36	6795.30	0	43929.06	10.41	0	50070.94

2004	early	52647.99	8369.23	0	44278.76	10.49	0	49721.24
2005	early	58446.51	9091.87	0	49354.65	11.69	0	44645.35
2006	early	49205.21	6007.83	0	43197.37	10.23	0	50802.63
2007	early	72255.00	12758.23	0	59496.77	14.09	0	34503.23
2008	early	84072.01	15446.16	0	68625.85	16.26	0	25374.15
2009	early	52850.64	6683.70	0	46166.94	10.94	0	47833.06
2010	early	75030.69	13678.40	0	61352.29	14.53	0	32647.71
2011	early	86638.77	15547.97	0	71090.80	16.84	0	22909.20
2012	early	62728.59	10182.07	0	52546.52	12.45	0	41453.48
2013	early	77566.51	13506.36	0	64060.15	15.17	0	29939.85
2014	early	81307.82	14590.98	0	66716.83	15.80	0	27283.17
1976	medium-late	79910.29	5650.40	47946.17	26313.72	6.23	0	67686.28
1977	medium-late	129815.99	0	129815.99	0	0	0	94000
1978	medium-late	116615.89	862.41	111951.25	3802.22	0.90	0	90197.78
1979	medium-late	83733.92	6697.73	46890.99	30145.20	7.14	0	63854.80
1980	medium-late	81295.36	12577.09	13007.26	55711.01	13.20	0	38288.99
1981	medium-late	124540.21	0	124540.21	0	0	0	94000
1982	medium-late	86133.06	15911.73	0	70221.33	16.63	0	23778.67
1983	medium-late	70303.99	12140.86	0	58163.13	13.78	0	35836.87
1984	medium-late	70489.76	2053.92	59211.40	9224.44	2.19	0	84775.56
1985	medium-late	92209.55	16984.21	0	75225.34	17.82	0	18774.66
1986	medium-late	93972.71	17307.28	0	76665.42	18.16	0	17334.58
1987	medium-late	77979.12	14264.03	0	63715.10	15.09	0	30284.90
1988	medium-late	133836.39	24708.47	0	109127.92	25.85	15127.92	0
1989	medium-late	101382.57	18724.69	0	82657.87	19.58	0	11342.13
1990	medium-late	69606.85	11689.13	0	57917.72	13.72	0	36082.28
1991	medium-late	48826.28	8711.13	0	40115.15	9.50	0	53884.85
1992	medium-late	113854.77	21016.87	0	92837.90	21.99	0	1162.10
1993	medium-late	80088.32	8881.83	32035.33	39171.16	9.28	0	54828.84
1994	medium-late	103092.00	12191.17	37113.12	53787.71	12.74	0	40212.29
1995	medium-late	78488.62	4865.14	50232.72	23390.76	5.54	0	70609.24
1996	medium-late	53623.24	9713.53	0	43909.71	10.40	0	50090.29
1997	medium-late	96289.87	17681.43	0	78608.44	18.62	0	15391.56
1998	medium-late	81911.81	14958.89	0	66952.92	15.86	0	27047.08
1999	medium-late	76624.94	10760.78	18389.98	47474.17	11.25	0	46525.83

2000	medium-late	86432.23	15596.85	0	70835.38	16.78	0	23164.62
2001	medium-late	62190.98	9440.01	0	52750.97	12.50	0	41249.03
2002	medium-late	74426.32	13704.74	0	60721.58	14.38	0	33278.42
2003	medium-late	48622.46	5904.93	0	42717.53	10.12	0	51282.47
2004	medium-late	49502.91	6231.55	0	43271.36	10.25	0	50728.64
2005	medium-late	56161.88	10367.54	0	45794.34	10.85	0	48205.66
2006	medium-late	45715.26	5885.42	0	39829.84	9.43	0	54170.16
2007	medium-late	71247.05	13026.09	0	58220.96	13.79	0	35779.04
2008	medium-late	86433.28	15741.88	0	70691.40	16.75	0	23308.60
2009	medium-late	51005.42	6624.86	0	44380.56	10.51	0	49619.44
2010	medium-late	84352.29	15320.96	0	69031.33	16.35	0	24968.67
2011	medium-late	88358.31	14868.13	0	73490.18	17.41	0	20509.82
2012	medium-late	66031.98	10954.12	2641.28	52436.58	12.42	0	41563.42
2013	medium-late	81051.66	10813.78	19452.40	50785.48	12.03	0	43214.52
2014	medium-late	87134.50	14366.81	6970.76	65796.94	15.59	0	28203.06
1976	late	94964.68	0	94964.68	0	0	0	94000
1977	late	129729.36	23975.28	0	105754.08	25.05	11754.08	0
1978	late	119063.57	10562.97	61913.06	46587.55	11.04	0	47412.45
1979	late	110538.31	0	110538.31	0	0	0	94000
1980	late	92631.85	18147.34	0	74484.51	17.64	0	19515.49
1981	late	139323.55	0	139323.55	0	0	0	94000
1982	late	106485.82	1572.36	97966.96	6946.51	1.65	0	87053.49
1983	late	81806.66	15042.63	0	66764.03	15.81	0	27235.97
1984	late	90549.16	669.48	86927.19	2952.49	0.70	0	91047.51
1985	late	100000.84	18469.32	0	81531.52	19.31	0	12468.48
1986	late	100756.94	16985.93	0	83771.01	19.84	0	10228.99
1987	late	81009.95	14313.04	3240.40	63456.52	15.03	0	30543.48
1988	late	143612.32	24094.54	5744.49	113773.29	26.95	19773.29	0.0
1989	late	122899.17	14467.03	0	108432.15	25.68	14432.15	0.0
1990	late	76900.26	14123.55	0	62776.71	14.87	0	31223.29
1991	late	54125.94	6544.71	18402.82	29178.41	6.91	0	64821.59
1992	late	126797.45	5624.48	96366.06	24806.91	5.88	0	69193.09
1993	late	88372.07	9777.71	35348.83	43245.53	10.24	0	50754.47
1994	late	109849.10	0	109849.10	0	0	0	94000
1995	late	96578.16	16413.32	7726.25	72438.59	17.16	0	21561.41
1996	late	61452.35	7334.48	12290.47	41827.40	9.91	0	52172.60

1997	late	103498.09	19130.50	0	84367.59	19.98	0	9632.41
1998	late	86954.58	7090.60	48694.57	31169.41	7.38	0	62830.59
1999	late	90206.11	13380.37	18041.22	58784.52	13.92	0	35215.48
2000	late	97707.23	18047.31	0	79659.92	18.87	0	14340.08
2001	late	67873.74	12258.04	0	55615.70	13.17	0	38384.30
2002	late	91193.32	16824.99	0	74368.33	17.62	0	19631.67
2003	late	53380.01	7360.66	0	46019.34	10.90	0	47980.66
2004	late	54063.81	7997.36	0	46066.45	10.91	0	47933.55
2005	late	61332.22	10007.15	0	51325.08	12.16	0	42674.92
2006	late	49564.00	6107.28	0	43456.72	10.29	0	50543.28
2007	late	79021.90	14155.80	0	64866.10	15.37	0	29133.90
2008	late	92131.45	11944.47	0	80186.98	18.99	0	13813.02
2009	late	55794.10	8602.31	0	47191.78	11.18	0	46808.22
2010	late	96992.16	17418.97	0	79573.19	18.85	0	14426.81
2011	late	92462.94	16831.49	0	75631.45	17.92	0	18368.55
2012	late	74046.66	12501.50	0	61545.16	14.58	0	32454.84
2013	late	88685.31	16849.17	0	71836.14	17.02	0	22163.86
2014	late	101575.52	9760.98	48756.25	43058.29	10.20	0	50941.71

CHAPTER 5

General conclusions

5.1 General conclusions

This PhD thesis explored the use of sorghum as a dedicated bioenergy crop (to generate electricity), and highlighted the benefits and risks associated with the use of early, medium-late and late sorghum genotypes.

The objectives and corresponding results achieved through this thesis are summarised here below:

- Objective 1. Explore the dynamics of the field drying process of three biomass sorghum genotypes characterized by different earliness (early, medium-late and late). This objective was reached with the use of a specific model, “sorghum haying model”. This model was developed in order to determine which sorghum genotype provides the best trade-off between biomass production and moisture content at baling time.

  The results showed that early sorghum genotype has the lowest average biomass production, but as it is harvested in a period that is favourable to on-field drying it has the shortest field drying period and the highest probability of being baled at a moisture content ≤ 18%. Therefore, despite the lower average production of early genotype with respect to medium-late and late genotypes, it provides farmers with a greater guarantee of successfully drying and baling the biomass. In addition to this, the shorter drying period also means that early genotype leaves the field earlier for the next crop in rotation and consequently optimize the agronomic practices of the farmers.

- Objective 2. Perform a risk assessment analysis to explore the risk related to producing a target amount of sorghum biomass (64000 Mg DM y^{-1}) using the early, medium-late and late genotypes. In addition a simplified energy balance, from cradle to farm gate, the energy performance of the three sorghum genotype was also determined by evaluating the following energy-based indices: Energy Return on Investment (EROI), Net Energy Gain (NEG) and Energy Use Efficiency (EUE). The CropSyst model, coupled with the sorghum haying model, was run on a mosaic of virtual farms distributed in the biomass sorghum supply area to simulate (I) the total biomass sorghum production, (II) biomass losses (mechanical and respiration losses) and (III) haymaking failure. As a final step amount of baled biomass available for the power plant was quantified.

  The simulation confirmed the findings of Chapter 2, that baled biomass, biomass losses and haymaking failure are significantly affected by genotype earliness.

  The highest incidence of the haymaking failure occurred with medium-late and late genotypes due to the adverse weather conditions during the field drying process.

The initial estimation of the number of hectares (4221.6 ha) results lower to achieve a percentage of 0.5 to exceed the 64000 Mg DM y^{-1}. For this reason the number of hectare have to be increased to 4557.9, 5159.6 and 4961.6 ha, respectively for early, medium-late and late.

Early genotypes had the highest energy performance in terms of EROI and NEG and had the lowest EUE. This is all due to the fact that early genotypes have the lowest incidence of haymaking failures, so despite their lower on-field production, they provide the highest volume of baled biomass.

Having the highest baled biomass, the highest energy performance and other advantages (e.g. an early genotype frees the field sooner than later ones, leaving more time for the subsequent crop) makes the earliest genotype the most favourable choice for biomass production, and it provides the highest probability of reaching the target production of 64000 Mg DM y^{-1} on the target area.

- Objective 3. A cradle to grave Life Cycle Assessments (LCA) and energy performance analysis of three different biomass supply chains fed by three sorghum genotypes of contrasting earliness (early, medium-late, late) complemented by cereal straw in covering full biomass power plant needs for electricity generation by combustion.

The results showed that late genotypes have the lowest GHG emissions (76.58 g $CO_{2eq.}MJ^{-1}_{el.}$) while medium-late and early genotype had a similar level of emissions (80.52 g $CO_{2eq.}MJ^{-1}_{el.}$ and 80.43 g $CO_{2eq.}MJ^{-1}_{el.}$, respectively). In all impact categories the power plant is the process that contributes most to the environmental emissions. The application of a $DeNO_X$ selective no-catalytic reaction (SNCR) system causes an increase between 23% and 45% in the climate change impact of the whole bioenergy systems. The non-inclusion of carbon emissions due to iLUC reduces the GHG emissions by 16%. Increasing or decreasing the SOC emission factor by 25% for both straw and sorghum changed GHG emissions by approximately 3%.

The results of the LCA study show that the late sorghum genotype reaches the lowest GHG emissions and should therefore be preferred to earlier genotypes when this impact category is considered. This result is in contrasts with those of Chapters 2 and 3 in which the early genotype was preferable considering its highest probability to be baled at a moisture content $\leq$ 18% (Chapter 2), its highest biomass baled which results in the highest probability to exceed the threshold of 64000 Mg DM y^{-1} (Chapter 3).

Low GHG emissions calculated for the late genotype are a consequence of its high haymaking failure (Chapter 3). Biomass left on field due to haymaking failure is in fact incorporated in the soil, thus increasing SOC, and mitigating the SOC decrease due to straw removal.

Overall, the results of this thesis contribute to improve the knowledge management of biomass sorghum from the field through to the end use, and can be used to help address the different productive, economical and environmental issues related to the use of sorghum biomass to produce electricity by direct combustion. In particular it is interesting to note that farmers and industry (bioenergy plant) will prefer the cultivation of early genotypes for the agronomic and logistic advantages described in Chapter 2 and 3 and until a specific retribution that takes into consideration the t overall GHG emissions of the system is not in place.

Appendix

List of publications

- Amaducci, S., Facciotto, G., Bergante, S., Perego, A., **Serra**, **P**., Ferrarini, A., Chimento, C. (2016). Biomass production and energy balance of herbaceous and woody crops on marginal soils in the Po Valley. *GCB Bioenergy*. doi: 10.1111/gcbb.12341.
- Ferrarini, A., Fornasier, F., **Serra**, **P**., Ferrari, F., Trevisan, M., Amaducci, S. (2016). Impacts of willow and miscanthus bioenergy buffers on biogeochemical N removal processes along the soil-groundwater continuum. *GCB Bioenergy*. doi: 10.1111/gccb.12340.

Other scientific activities

Review of literature

Biomass production from annual and perennial bioenergy crops, environmental impact and energy performance of bioenergy systems (December 2013 – June 2014)

Field activities

Installation of three bioenergy buffers field trials in northern Italy (March 2013- June 2013). The bioenergy buffers are composed by perennial herbaceous (switchgrass, *Panicum virgatum*; miscanthus, *Miscanthus per giganteus* L.) and woody crops (black locust, *Robinia pseudoacacia*; willow, *Salix matsudana*)

Estimation of biomass production from dedicated biomass cultivated in the bioenergy buffers.

Writing of project proposal

LIFE13 ENV/IT/001192 project: "*Implementation of Bioenergy Buffer Strip networks and Innovative Sustainable Cropping Systems in Agroecosystem Planning*" (May 2013 - July 2013)

Working visits (PhD period abroad)

Joint Research Center (JRC), Institute for Energy and Transport, IET (Supervisors: Alessandro Agostini and Jacopo Giuntoli), Petten, The Netherlands (January-March 2014 and September-December 2014)

Topic: Environmental impact and energy performance analysis applied to bioenergy systems.

Objective: To perform a Life Cycle Assessment (LCA), using Gabi software, to evaluate the environmental impact and energy performance of biomass sorghum to generate electricity by direct combustion in a biomass power plant in the Po Valley (northern of Italy).

Courses/training

GABI software training. Joint Research Center (JRC), Ispra (VA) Italy (February 2015).

PhD exams of the doctoral school (November 2012- February 2013)

- Sustainable animal production - Sustainable crop production
- Agricultural and food policies of the EU
- Scientific communication
- English course
- Food technology and sustainability
- Nozioni giuridiche fondamentali concernenti la disciplina del sistema agroalimentare
- Dal diritto dell'agricoltura al diritto alimentare

- Diritto europeo multi-livello e disciplina agroalimentare
- Nutrizione umana
- Research ethics and epistemology
- Research project and research programs
- Statistics and data management
- Diritto internazionale ed europeo del commercio dei prodotti agroalimentari
- Basic management of knowledge

Poster presentation at international symposia, workshop and conferences

- Ferrarini, A., **Serra**, **P**., Trevisan, M., Amaducci, S. Linking bioenergy and ecological services along field margins: the HEDGE-BIOMASS project proceedings of the 22nd European Biomass Conference & Exhibition, 23-26 June 2014, Hamburg, Germany
- Ferrarini, A., **Serra**, **P**., Trevisan, M., Puglisi, E., E., Amaducci, S., 2012. Managing Bioenergy Production on arable field margins for Multiple Ecosystem services: Challenges and Opportunities. European Geosciences Union (EGU), April 7-12, 2013, Wien, Austria
- Amaducci, S., **Serra**, **P**., Tabaglio, V. *Valutazione degli effetti della coltivazione di sorgo da biomassa sulla nutrizione azotata del frumento*. XLI National Congress of the Italian Society of Agronomy (SIA), 19-21 September 2012, Bari, Italy

Attendance to international/national congress

- **Serra**, **P**., Agostini, A., Giuntoli, J., Colauzzi, M., Amaducci, S. Risk assessment and GHG emissions mitigation potential of bioelectricity from energy sorghum. 23nd European Biomass Conference & Exhibition, 1-4 June 2015, Vienna, Austria. (*oral presentation*).

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Grazie davvero a tutti

Curriculum vitae

Paolo Serra was born in Broni, Italy, on January 12th, 1985. He composed his secondary education at Istituto Tecnico Agrario Statale (ITAS), "Carlo Gallini" (Voghera Italy) in June 2004 with 82/100 obtaining the title of land surveyor. From January 2005 to July 2006, he started to work, as quality controller of rice samples for "Cooperativa Smeralda" (Broni, Italy) partner of rice factory "Riso Scotti" (Pavia, Italy). From October 2006 to January 2010 he obtained his first level degree in "Agricultural Science and Technology" at the Università Cattolica Del Sacro Cuore (UCSC), Piacenza Italy. The title of the thesis was "The industrial transformation of rice: Qualitative aspects" under the supervision of Stefano Amaducci, Professor of Field crops and Non-food crop production. After obtaining bachelor's degree with 109/110, in January 2010, he started the second level degree in "Agricultural Science and Technology" (curriculum: Plant Production and Protection Crops) at the Università Cattolica Del Sacro Cuore (UCSC, Piacenza Italy). He graduated in April 2012 with 110/110 (cum laude). The title of the thesis was "Evaluation of the effects of the cultivation of biomass sorghum on nitrogen nutrition of wheat" and his supervisor was the Prof. Dr. Stefano Amaducci. From May 2012 to September 2012 he participated to an experimental trials in the Po Valley (northern of Italy) called "Analysis of risk relative to the cultivation of biomass sorghum to generate electricity by direct combustion in a biomass power plant" commissioned by Lombardia Region where the Prof. Dr. Stefano Amaducci was the scientific supervisor. The scope of experimental trials was to evaluate the production performance, of three biomass sorghum genotypes characterized by different earliness (early, medium-late and late), to feed a biomass power plant to generate electricity by direct combustion the biomass. In November 2012 he started his PhD in the Agrisystem Doctoral School (UCSC, Piacenza, Italy) at the Department of Sustainable Crop Production (tutor: Prof. Dr. Stefano Amaducci). The PhD project (Hedge-Biomass project) was focused on the assessment of the biomass production, environmental impact, energy performance and logistics optimization of the perennial herbaceous and woody crops cultivated in buffer strips. From January-March 2014 and from September-December 2014 he spent his PhD period abroad at Joint Research Center, Institute for Energy and Transport, (JRC-IET), Petten, The Netherlands. During this period, under the supervision of Alessandro Agostini and Jacopo Giuntoli, he conducted and Life Cycle assessment (LCA) using Gabi software (Thinkstep) with the aim to explore the environmental and energy performance of biomass sorghum to generate electricity by direct combustion in a biomass power plant in the Po Valley (northern Italy). During PhD period he gained skills in the fields of LCA (software: Thinkstep GaBi) and crop modelling (CropSysts).

He participated at the 23rd European Biomass Conference & Exhibition (1-4 June 2014, Vienna, Austria) giving an oral presentation entitled "Risk assessment and GHG emissions mitigation potential of bioelectricity from energy sorghum".

In 2016 he will spend a training period of six mount at Joint Research Center, Institute for Energy and Transport, (JRC-IET), Petten, The Netherlands with the aim to development a complete LCA and energy assessment of perennial biomass crops cultivation in bioenergy buffer strips under the supervision of Alessandro Agostini and Jacopo Giuntoli.

He will participate at 24th European Biomass Conference & Exhibition (6-9 June 2015, Amsterdam, The Netherlands) presenting an oral presentation entitle "Environmental and energy assessment of biomass crops cultivation in bioenergy buffer strips".