Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Bioenergy feedstock production on abandonned agricultural land in Europe

A spatially explicit life cycle analysis

Master's thesis in Industrial Ecology
Supervisor: Francesco Cherubini
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Abstract

Abandonned agricultural land have emerged as the most promising areas for the production of bioenergy that would minimize land use competition with food and associated negative social and environmental impacts. Here, we investigate the spatial variability of the environmental performance from the large scale production of bioenergy feedstock from three promising perennial crops grown on abandonned cropland in Europe. Different water supply and harvest timing are consisered and compared to identify practices that could minimize the environmental impact. Finally, this work explores the potential and variability of soil carbon sequestration from biomass production. Using the LCA methodology and spatially explicit yield and water requirements estimates from GAEZ, life cycle impacts are computed for abandonned cropland in Europe at a spatial resolution of 5 arcminutes. Results show that switchgrass generally hold the greatest biomass production potential for Europe alongside with the lowest environmental impact per ton produced. Irrigation increases biomass production potential by 131% on average at the cost of a 300% increase in climate change impact. Delaying harvest in the other hand improves environmental performance per ton of dry matter produced. This work identified areas of central Europe surrounding mountains and areas in the north-east of Europe to show the best biomass production efficiency (lowest impact per ton produced). Areas of north-east Europe also coincide with high soil carbon sequestration potential. Results reported here support the findings that irrigation should generally be avoided for bioenergy production [1] and that delayed harvest improves environmental performance at the cost of large decrease in yield (29% on average). Future research should concentrate on developing more reliable estimates of soil organic carbon changes under perennial crops so that they can systematically be included in life cycle analysis. Better accounting for the spatial variability of nutrient requirements, especially nitrogen also appears crucial in identifying areas with high potential and low environmental impacts.

Sammendrag

Forlatte jordbruksareal har vist seg som de mest lovende områdene for produksjon av bioenergi som vil minimere konkurranse med arealbruk med mat og tilhørende negative sosiale og miljømessige konsekvenser. Her undersøker vi den romlige variasjonen i miljøytelsen fra storskala produksjonen av bioenergi råstoff fra tre lovende flerårige avlinger dyrket på forlatt avlingsland i Europa. Ulike vannforsyning og høstingstidspunkt er konsisert og sammenlignet for å identifisere praksis som kan minimere miljøbelastningen. Til slutt utforsker dette arbeidet potensialet og variasjonen i karbonbinding i jord fra biomasseproduksjon. Ved å bruke LCA-metodikken og romlig eksplisitte estimater for avkastning og vannkrav fra GAEZ, beregnes livssykluspåvirkningene for forlatt avlingsland i Europa med en romlig oppløsning på 5 buminutter. Resultatene viser at switchgrass generelt har det største biomasseproduksjonspotensialet i Europa sammen med den laveste miljøpåvirkningen per produsert tonn. Irrigasjon øker potensialet for biomasse med 131% i gjennomsnitt til en kostnad av 300% økning i klimaendringseffekten. Forsinkelse av høsting på den annen side forbedrer miljøytelsen per tonn produsert tørrstoff. Dette arbeidet identifiserte områder i Sentraleuropa som omgir fjell og områder nordøst i Europa for å vise den beste biomasse produksjonseffektiviteten (laveste påvirkning per produsert tonn). Områder i Nord-Øst-Europa faller også sammen med et høyt karbon-sekvestreringspotensial. Resultatene som er rapportert her, støtter funnene om at vanning generelt bør unngås for bioenergiproduksjon [1 23] og at forsinket høsting forbedrer miljøprestasjonen til en pris av stor nedgang i utbyttet (29% i gjennomsnitt). Fremtidig forskning bør konsentrere seg om å utvikle mer pålitelige estimater av jordiske organiske karbonforandringer under flerårige avlinger, slik at de systematisk kan inkluderes i livssyklusanalyse. Bedre redegjørelse for den romlige variasjonen i næringsstoffbehov, spesielt nitrogen virker også avgjørende for å identifisere områder med stort potensial og lite miljøbelastning.

Preface

I would like to thank my supervisor Francesco Cherubini for his guidance throughout the project. The time he dedicated to our meetings and the consideration showed for my work was highly appreciated. My particular thanks go to my co-supervisor Cristina Maria Iordan for her patience and involvement 24/7 during the year. She supported me throughout the project and encouraged me every step of the way. She also recruited Otávio Cavalett who greatly helped me in compiling a sensible life cycle inventory. Together, they helped me daily in getting and understanding the results presented in this report. Finally, I would like to thank my second co-supervisor Jan Sandstad Næss for the time he dedicated to my project. He provided most of the background data used in this work and was there to answer my questions every time I needed.

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Table of Contents

1 List of Figures VI

2 List of Tables VII

3 List of Abbreviations (or Symbols) VIII

1 Introduction 1

1.1 Background and motivation 1

1.2 Problem description 4

1.2.1 Research questions 4

1.3 Structure 5

2 Methods 6

2.1 Yield potential on abbandonned aggicultural land 6

2.1.1 Mapping abandonned agricultural cropland 6

2.1.2 Biomass yield model 7

2.1.3 Biomass yield on abbandonned agricultural lands 9

2.2 Life cycle inventory framework 10

2.2.1 Goal and scope definition 10

2.2.2 Life cycle inventory 11

Stand lifetime 11

Agricultural operations 12

Agricultural inputs 21

Agricultural outputs and residue production 29

Emissions to air and water 33

SOC stock changes 37

Process and input modelling 39

2.3 Life cycle Impact assessment 40

2.3.1 Choice of impact categories and method 41

2.3.2 Impact assessment routine 41

3 Results and discussion 43
3.1 Preliminary discussion 43
3.2 Environmental performance for Europe 44
3.2.1 Inputs and Outputs 44
3.2.2 Total European impact breakdown 46
3.2.3 Total European impact 49
3.2.4 Average impact per tDM 50
3.3 Environmental performance – Spatial variability 52
3.3.1 Influence of different agricultural system on the spatial variability 52
3.3.2 Impact maps 56
3.4 Benefits and tradeoff from different agricultural system 59
3.4.1 Benefits from delaying harvest – CC 59
3.5 Soil organic carbon changes 61
3.5.1 First approach 61
3.5.2 Second approach 63
3.6 Limitations 65
3.6.1 Yield estimates 65
3.6.2 Nutrient requirements 66
3.6.3 Influence of the harvest timing on the agricultural system 66
3.6.4 Irrigation modelling 67
3.6.5 Soil organic carbon 68
4 Conclusion 70
5 References 72
6 Appendices 88

1 List of Figures

Figure 1: Identified abandoned agricultural land in Europe (ha) 7
Figure 2: Modelled maximum agro-climatic harvested yield 9
Figure 3: Schematic of Life cycle analysis system boundaries for biomass production 10
Figure 4: Impact estimation procedure 42
Figure 5: Relative contribution of key elements to the total European LCA impact............. 47
Figure 6: Life cycle impact per cell from the production of biomass.................................... 53
Figure 7: Life cycle impact from the production of 1 t dry biomass 55
Figure 8: Life cycle climate change impact from the production of 1 tonne of biomass 57
Figure 9: Total life cycle climate change impact from the production biomass..................... 58
Figure 10: Changes in climate change impact per ton of dry matter from delaying harvest .. 60
Figure 11: Soil organic carbon stock changes under perennial crops to a depth of 100cm. ... 61
Figure 12: Relative soil organic carbon changes under perennial crops for different stand age. 63

2 List of Tables

Table 1: Comparative characteristics of miscanthus, switchgrass and reed canarygrass. 3

Table 2: Life cycle field operations for growing and harvesting biomass 13

Table 3: Average yearly agricultural operation for one hectare of land 20

Table 4: Above ground biomass composition at harvest time 22

Table 5: Herbicide application rates 25

Table 6: Average yearly input requirement for one hectare of land 28

Table 7: Senesced residue composition 31

Table 8: Belowground residue composition 32

Table 9: Nitrate leaching from the different sources of nitrogen addition to soil. 36

Table 10: Direct and indirect nitrous oxide emissions. 37

Table 11: fuel consumption and machinery characteristics for field operations 40

Table 11: Bioenergy feedstock yield potential in Europe 43

Table 13: Main characteristics of the different scenario 44

Table 14: Total European impact for different scenarios 49

Table 15: Average European life cycle impact from the production of one ton of dry biomass 50

3 List of Abbreviations (or Symbols)

CCS	Carbon Capture and Storage
SSP	Shared Socio-economic Pathways
RCP	Representative Concentration Pathway
MSC	Miscanthus
SWG	Switchgrass
RCG	Reed canarygrass
LCA	Life Cycle Analysis
SOC	Soil Organic Carbon
GHG	Greenhouse Gas
LC	Land Cover
ESA CCI	European Space Agency Climate Change Initiative
GAEZ	the Global Agro-Ecological Zones
IIASA	the International Institute for Applied Systems Analysis
FAO	Food and Agriculture Organization
USDA	United States Department of Agriculture
DEFRA	Department for Environment, Food and Rural Affairs
TEAGASC	Agriculture and Food Development Authority
PLS	Pure Live seeds
a.i	Active ingredient
IPCC	Intergovernmental Panel on Climate Change
PM	Particulate Matter
NMVOC	Non-methane volatile organic compounds
TSP	Total Suspended Particles
EMEP	European Monitoring and Evaluation Programme
EEA	European Environment Agency
LUC	Land Use Change
LU	Land Use
CC	Climate change
TA	Terrestrial Acidification
FE	Freshwater Eutrophication
ME	Marine Eutrophication
FRS	Fossil Ressource Scarcity

1 Introduction

1.1 Background and motivation

In 2019, bioenergy supplied about 10% of the world's total primary energy [2]. Looking at future projections, bioenergy production is expected to increase significantly during the next century to support climate change mitigation strategies and increased energy demand [3, 4]. Indeed, most ambitious climate change mitigation strategies rely on fast, large scale deployment of biomass energy, often in combination with Carbon Capture and Storage (CCS) [4, 5]. Second generation bioenergy crops, especially, are expected to play a key role as they provide opportunities to cut emissions in the electricity and transport sectors while allowing for atmospheric carbon removal with CCS [3]. The different Shared Socio-economic Pathways (SSP) suggest that bioenergy feedstock demand could range ~5300 to 23000 million tons of dry matter per year by the end of the century to meet the RCP 2.6 mitigation target [3]. Accordingly, model estimates that 245 to 1517 million hectares would need to be allocated to dedicated bioenergy crops, resulting in large changes in the land use patterns with implications for food production system [3, 5, 6].

Besides climate change mitigation, land use is at the nexus of other key challenges for the century, among others, feeding the increasing global population and protecting natural ecosystems [3, 6, 7]. In the past years concerns have been raised regarding the development of bioenergy with the identification of sustainability trade-off [8]. The additional demand for land could trigger direct and indirect land use changes that could compromise the very mitigation potential of bioenergy [9-11]. More generally, increased competition with other land use is a threat to food security and natural ecosystems [8, 12-14].

Using abandoned agricultural lands for bioenergy production has recently emerged as a sustainable approach that would minimize land competition and consequent adverse effects [13, 15, 16]. Agricultural abandonment, is a widespread, growing trend in many regions of the world, including Europe [17, 18]. It is driven by a combination of socio-economic, political and environmental factors that undermines the economic viability of formerly cultivated fields. Targeted incentives could however stimulate the production of bioenergy on those lands with potential environmental and social benefits [19-21].

High yielding, perennial rhizomatous grasses such as Miscanthus (Miscanthus spp), Switchgrass (Panicum virgatum) and Reed canarygrass (Phalaris arundinacea) are promising candidates for bioenergy production on abandoned lands [22]. These crops have extensive rooting systems that allows for high water use efficiency and recycling of nutrients over the years [23]. Their perennial nature also reduces tillage and maintenance operation needs [23]. Accordingly, these crop exhibit high yield for low costs and input requirements [23, 24]. In addition, established stands were also found to have positive environmental impacts such as reduced soil erosion, improved soil quality and increased biodiversity by providing habitat for wildlife [21, 25, 26]. Reduced soil disturbance from limited tillage, along with large amount of aboveground residue production, is also expected to benefit soil organic carbon which could further increase their mitigation potential [23, 27, 28].

The genus miscanthus consist of 17 species of C4 grass originated from south East Asia [29]. Today, the genotype most widely used for bioenergy production in Europe is the sterile hybrid Miscanthus×giganteus [30]. Its parents, Miscanthus×sinensis and Miscanthus×sacchariflorus however, were also identified as potential high yielding bioenergy crops [31]. M. Giganteus can grow up to four meters tall and produces roots that can reaches a depth of three meters [32]. It has high persistence and can grow under a wide range of climatic conditions, maintaining high productivity at low temperatures [33, 34]. Today, miscanthus is a rather unimproved crop and large improvement both in terms of climate adaptability, resistance and yield can be expected in the future from breeding efforts [24].

Switchgrass is a C4 grass originated from North America [30]. Occurring naturally from Canada to Mexico, it has adapted to a large variety of agro-climatic conditions ranging from prairies to brackish marshes and open woodlands [30]. Switchgrass grows up to three meters tall and develops roots down to three to four meters deep [35]. Previous experiments have shown that it would be possible to find switchgrass varieties adapted to most regions of Europe.

Finally, reed canary grass is a coarse, vigorous and rhizomatous C3 cold season grass distributed throughout Europe, Asia and temperate regions of North America. [36-39]. Reed canary grass holds high yield potential and perform better than C4 grasses such as miscanthus and switchgrass in cold regions [40]. The crop is interesting for Europe because it is indigenous and presents high genetic variability and adaptability to local climate conditions [30, 41]. Reed canary grass growth up to two meters tall and has roots down to two meters deep.

In Europe, miscanthus and switchgrass generally show better yield than reed canarygrass [42]. Due to their alternative photosynthetic pathways, C4 grasses also have higher nutrient and water use efficiency [42]. In northern regions of Europe however, and despite the noteworthy cold tolerance of miscanthus and switchgrass, cold winter temperatures remain a major limitation to their establishment and growth [42]. Generally speaking, while some limitation exists, all three crops display high yield potential over a wide variety of climate, making them attractive bioenergy crops among perennial rhizomatous grasses. Another important feature is that all three can easily be incorporated into the existing farming system as conventional equipment can be used [30, 43]. Table 1 provides a comparison of the three crops upon characteristics of particular relevance for bioenergy production. In several countries of Europe, large scale production of perennial bioenergy crops has already started and miscanthus is commercially cropped in Ireland, Italy and the United Kingdom [31]. Reed canarygrass in the other hand is widely cropped in Finland [31].

Table 1: Comparative characteristics of miscanthus, switchgrass and reed canarygrass.

Latin name	**Miscanthus ssp**	**Phalaris Arundinacea**	**Panicum Virgatum**
Photosynthetic pathway	C4	C3	C4
Soil	Wide range	Wide range	Wide range
pH	5.5-8.0	4.9-8.2	5.0-8.0
Water supply	Not tolerant to stagnant water and prolonged drought	Drought tolerant and tolerant to wet areas	Drought tolerant Moderately tolerant to flooding
Yield range in Europe (tDM.ha-1)	5-49	7-16	5-23

Based on [30, 44-48]

The pressing issue of climate change and the heavy reliance of stringent mitigation pathways on bioenergy are promoting their development worldwide with uncertain environmental outcomes. It is becoming increasingly important to better understand their overall environmental performance in order to accurately quantify their mitigation potential and inform policies. Life cycle analysis (LCA) is a method for assessing environmental performance of products by systematically accounting for the environmental impact that arise over their full life cycle, including raw material acquisition, production, use and disposal. LCA can serve a critical role in the development of sustainable bioenergy by linking specific environmental impacts to key elements of the production process and identifying levers for environmental performance improvement.

In the past years, several studies have explored the life cycle performance of miscanthus [49-54], switchgrass [55-57] and reed canarygrass [58] or combinations of them [59-61]. However, most of these studies considered the cultivation of perennial crops on agricultural cropland. In contrast, few studies have looked at their performances when grown on marginal or abandoned land [1, 62, 63]. To date, there is no study focusing on perennial grasses grown on abandoned land across Europe.

1.2 Problem description

The main purpose of this study is to provide a cradle to farm gate life cycle assessment of bioenergy feedstock production on abandoned agricultural land in Europe. The area of interest covers the longitudes range [-24,48], and latitudes range [34,72]. A recent estimate of the spatial distribution and extent of abandoned agricultural land is used along with a global yield model to estimate bioenergy feedstock potential on abandoned agricultural land. Three perennial crops are considered due to their particularly interesting features for bioenergy production: miscanthus, reed canarygrass and switchgrass. Two irrigation scenarios are considered (rainfed and irrigated) along with two harvest management systems (early and late). In total four scenarios are considered for each crop in order to compare their environmental performance and identify potential key factors for sustainable cultivation of perennial biomass crops. Soil organic carbon (SOC) changes following land use change to perennial energy crops are also investigated as their importance for accurately estimating GHG balance of bioenergy crops was repeatedly pointed out [64].

1.2.1 Research questions

This thesis aims to answer the following research questions:

- What are the environmental performance of bioenergy feedstock production from perennial grasses grown on abandoned agricultural land in Europe, and how do they vary spatially?
- Can irrigation and changes in the harvest timing improve the environmental performance of bioenergy crops?
- How does SOC stock respond to land use change to perennial grasses and how can these changes affect the environmental performance of bioenergy feedstock?

1.3 Structure

This thesis follows a traditional structure based on the IMRaD model: Introduction, Methodology, Results and Discussions. Following the introduction of the topic and the study goal, the methodology applied to answer the research questions is presented. The methodology describes the data foundation and provides a detailed description of the approach used to prepare and analyse them. Results are presented and discussed together in a third part of this report. Limitations, area of uncertainty and recommendation for future work are presented in a final section, along with closing remarks.

2 Methods

This chapter details the different steps and assumptions used in this analysis to compute and create life cycle impact maps from bioenergy feedstock production from perennial crops grown on abandoned land in Europe. The first section (p 6-9) presents the method used to identify abandoned land and estimate site-specific yield potential and irrigation volume requirements. The second section (p10-41) presents the life cycle inventory compiled for this work. The inventory is spatially explicit as it varies following the spatial variables yield and irrigation requirement. The inventory is also scenario specific as two harvest system and two irrigation levels are considered for each crop. Finally, the third section (p40) details the method used to compute cell-specific impact and create impact maps with a 5 arcminute spatial resolution.

2.1 Yield potential on abbandonned aggicultural land

Here is presented the method used to create maps of potential yield from perennial grasses grown on abandoned agricultural land in Europe. This is done in three steps: first abbandonned lands across europe are identified and mapped, second, yields are estimated for the entire European area, third, information are combined to produce maps of yield potential on abbandonned land.

2.1.1 Mapping abandonned agricultural cropland

Abandoned agricultural cropland maps for Europe (Figure 1) were obtained from (Næss, Cavalett, 2020). The authors identified abandoned cropland at a global scale by comparing Land Cover (LC) maps from the European Space Agency Climate Change Initiative (ESA CCI) project between 1992 and 2015 [66]. The ESA CCI-LC dataset provides annual global maps of the earth’s terrestrial surface at 300m spatial resolution using 37 land classes based on the United Nation Land Cover Classification System. In their work, (Næss, Cavalett, 2020) considered all transition from one of the six cropland classes to any other classes except from urban and other cropland as abandoned cropland. Results are global abandoned cropland maps in hectares at five arcminutes spatial resolution. European maps were further extracted and are presented in Figure 1.

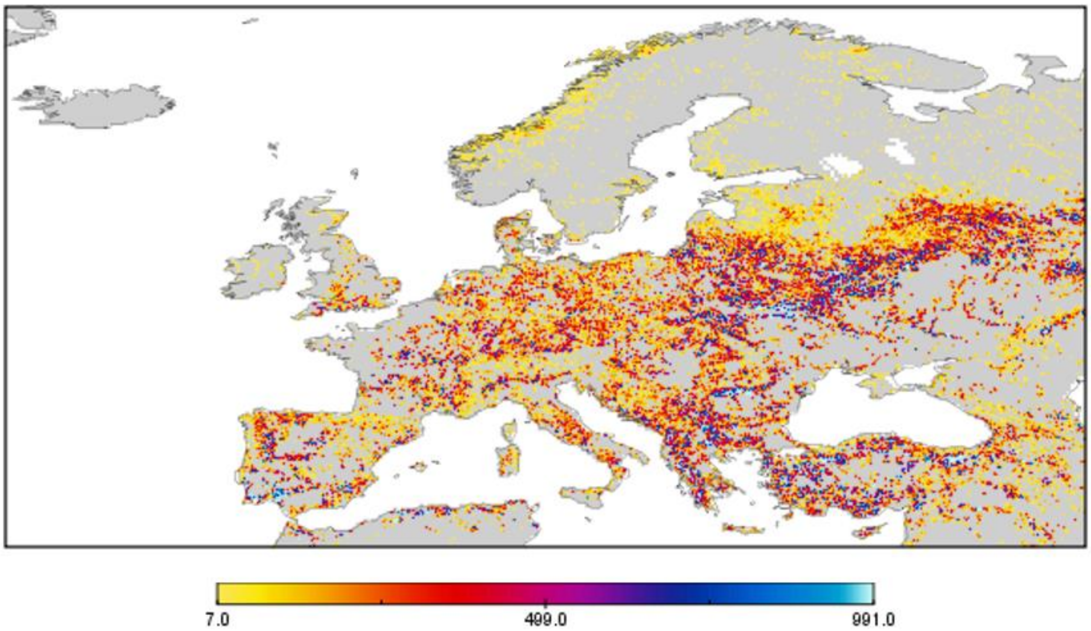

Figure 1: Identified abandoned agricultural land in Europe (ha) – Values ranging from 3ha to 4874ha. Scale based on the 5th (7ha) and 95th (991 ha) quartiles

2.1.2 Biomass yield model

Bioenergy crop yields (dry mass) for the three selected bioenergy crops in Europe were also obtained from (Næss, Cavalett, 2020). The authors used the Global Agro-Ecological Zones (GAEZ) model version 3.0 [67] to estimate maximum agro-climatic yields of miscanthus, switchgrass and reed canarygrass grown for bioenergy production at a global level. The GAEZ model was developed in a collaborative effort by the International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization of the United Nations (FAO). It has been widely used in the past to model productivity[68-70] and water consumptions from irrigation [71] for a variety of crops. More recently, the model has been applied to estimate bioenergy potential in the world [65, 72, 73], and in Europe [74].

GAEZ uses geo-referenced climatic, soil and terrain datasets to evaluate site-specific crop yields and water use with a resolution of five arcminutes. The model proceeds in three major steps. First it evaluates whether it is feasible to grow a particular crop in a particular location considering local biophysical constrains (temperature, annual rainfall, soil…) and crop characteristics (photosynthetic rate, growth cycle length…). Second, the model evaluates maximum agro-climatic yields under ideal conditions for a given agricultural production system. Third, the potential yield is modified to account for agro-climatic constrains (harvest efficiency, pests, yearly climate variability…). Additionally, the model computes site specific crop water balance and annual water deficit under rainfed conditions.

Yields can be estimated for three different agricultural production systems defined by a combination of 3 input levels (low, medium and high) and 2 water supply levels (rainfed and irrigated). High input levels depicts a modern agricultural management scheme, mainly market oriented with full mechanization and optimal use of fertilizer and pesticides. Low input level refers to traditional farming practices with no mechanization, fertilizers or herbicides and medium input level falls in between. As opposed to rainfed conditions, irrigated conditions assumes no water deficit during the crop growth cycle. In addition, the model allows for the use of different climate dataset to estimate productivity under future climate projections.

Six of the scenarios developed by (Næss, Cavalett, 2020) are considered in this work. As this study focuses on Europe, a high input agricultural production system is considered for the three crops. Indeed, low and medium input levels are not believed to be representative of the European farming practices. However, both rainfed and irrigated scenarios were investigated. As for the climate projections, yields were modelled for the year 2020, assuming a RCP4.5 scenarios. This scenario is typically associated with a 2.4˚C increase of the mean annual temperature by 2100 relative to preindustrial times [75]. (Næss, Cavalett, 2020) obtained future climate conditions from the HadCM3 model [76].

Figure 2 presents bioenergy crop yield estimates from GAEZ as found in (Næss, Cavalett, 2020), for the entire European area under both rainfed and irrigated conditions.

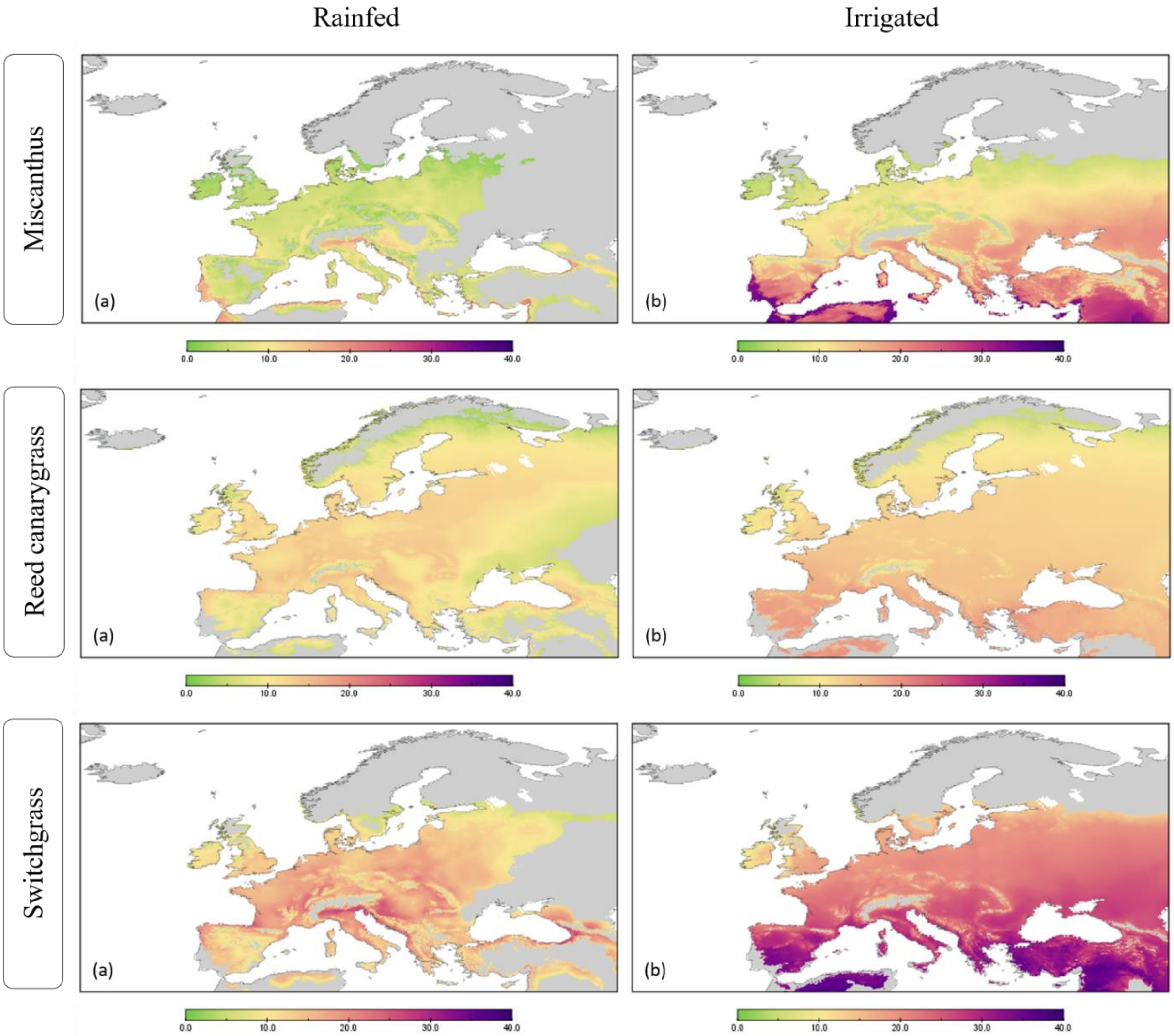

Figure 2: Modelled maximum agro-climatic harvested yield of miscanthus, reed canarygrass and switchgrass in 2020 in Europe at the end of the growing season under high input management. (a) Potential non-water limited yield and (b) Potential rainfed yield. (tDM/ha).

2.1.3 Biomass yield on abbandonned agricultural lands

Estimated biomass yield for Europe (Figure 2) and abandoned agricultural cropland were then combined as detailled in (Næss, Cavalett, 2020) to create maps of potential bioenergy crop yields from abandoned cropland (data shown in Appendix 1).

2.2 Life cycle inventory framework

This section presents the main assumptions used in this study to create a life cycle inventory for three different crops that depends on two spatial variables (yield potential and irrigation requirement), two irrigation level (rainfed and irrigated) and two harvest timing (early harvest and late harvest).

2.2.1 Goal and scope definition

This work intent to evaluate the environmental performance of the production of biomass from miscanthus, switchgrass and reed canarygrass grown on abandoned agricultural lands in Europe by using a life cycle perspective. Different management systems are investigated in order to compare their environmental performance and identify potential key factors for sustainable cultivation of perennial biomass crops. Finally, this work explores the relationship between the spatial variability of biomass yield and environmental impacts.

Figure 3 represent a typical agronomic system for the production of biomass from perennial energy crops in Europe. The system boundaries (Figure 3) include all processes required for biomass production and delivery at farm gate. The foreground system comprises all on-field processes (ie: agricultural steps happening in the field itself) while processes occurring further upstream were included in the background system and modelled using generic data. Infrastructures were not included in the inventory, except for background data. Storage was also excluded from the analysis despite the large volume of biomass considered. Indeed, storage time and storage conditions are expected to be dependent on the final use of the biomass which was excluded from the analysis. On farm transport of input and biomass, on farm travel of agricultural machinery and preliminary work at the farm were also excluded from the inventory.

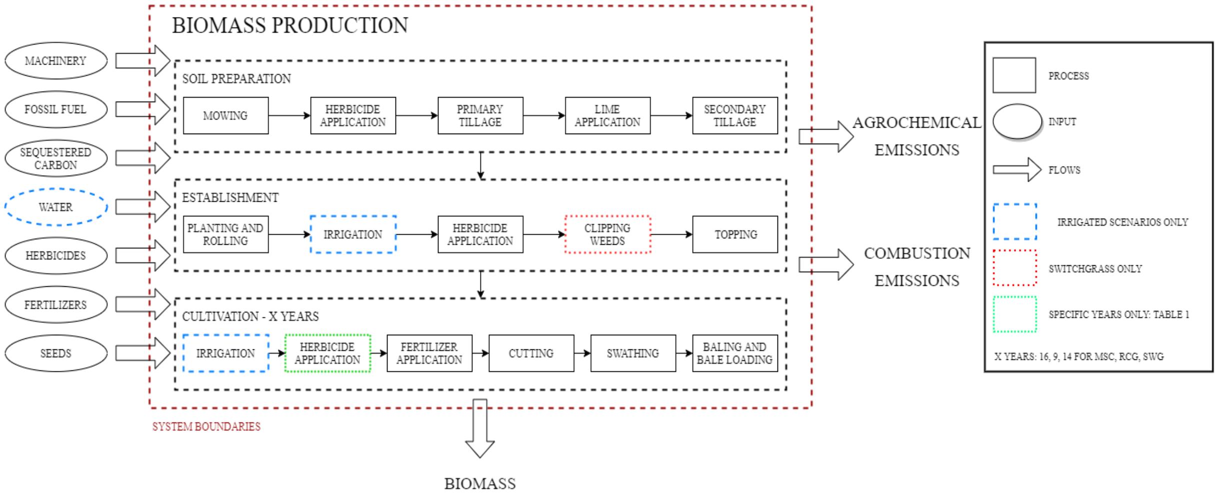

Figure 3: Schematic of Life cycle analysis (LCA) system boundaries for biomass production

Soil organic carbon (SOC) changes were included but treated separately due to the large associated uncertainty. SOC changes were modelled considering cropland as the agricultural reference system. However, as the study focuses on abandoned agricultural lands, direct and indirect land use changes were excluded from this analysis. Finally, agricultural steps related to the crop destruction are not included in the inventory. Indeed, this work assumes a steady state system were the same crop is replanted at the end of the stand's lifetime. In such conditions, crop destruction and soil preparation for the new stand merge and are attributed to the new stand. In the context of a continuous cropping system, the functional unit of this life cycle inventory is 1 ha of land cultivated for 1 year for biomass production. The life cycle inventory for 1 hectare cultivated for one year is obtained by discounting the total requirement for the lifetime of a stand by the lifetime of the stand.

2.2.2 Life cycle inventory

A crop-specific life cycle inventory was compiled for the culture of miscanthus, reed canarygrass and switchgrass at a European scale under both irrigated and rainfed conditions. In addition, two harvest timing are considered, bringing to four, the number of scenario considered for each crop. As previously explained, data collected here corresponds to a high input agricultural system. The compiled inventory is spatially variable as it depends on the yield and water stress level of a particular locations, both obtained from GAEZ. Indeed, yield is a determining factor for several key processes such as fertilizer use, biogenic emissions from residues and harvest fuel consumption. Similarly, local water stress levels are taken in this work as irrigation requirement and are the only driver behind water and energy consumption from the irrigation process. Data used in the inventory were primarily obtained from international scientific journals and publications from scientific institutions. Reports issued by European institutions and governments were also used as data sources, along with reports from private entities available to the public. Doctoral theses were used occasionally when no other source of data could be found. Finally, the Ecoinvent database version 3.0 was used as the main source of data for modelling background processes.

Stand lifetime

This analysis assumes a lifetime of 17, 10 and 15 years for miscanthus, reed canarygrass and switchgrass respectively. As for now, there is no consensus on the lifetime of these three crops grown for bioenergy production [77]. An estimate was derived from field trials observations, estimates and assumptions reported in the reviewed literature.

Earlier work concluded that miscanthus productivity could be maintained up to 25 years [30], however, long term field trials have shown a decrease in miscanthus yield with stand age [47, 78]. Recent work generally assumes lower lifetime, typically ranging between 15 and 20 years. Based on the reviewed literature, a lifetime of 17 years was assumed which is considered to be a conservative but realistic estimate.

For reed canarygrass, while (Pahkala, Aalto, 2008) reported that stands in Sweden had maintained their yields over 16 years, trials in Ireland have shown low stand persistence after four years [80]. The authors concluded that under such conditions, reed canarygrass stands would need to be replanted every three to five years. Three of the reviewed studies considered lifetime superior to 10 years while 4 considered lifetime inferior or equal to 10 years. A conservative estimate of 10 years was adopted in this work.

Finally, reported lifetime for switchgrass stands range from 5 to 20 years [81, 82]. Lowest estimates were reported in Canada where new diseases affecting switchgrass (head smut, anthracnose…) have been reported and are expected to increase in severity in the future as the area planted with switchgrass increases [81]. However, no serious disease has yet been reported in Europe and recent estimates for European conditions under proper management range between 10 and 20 years [59, 60, 82, 83]. In agreement with these observations, the assumed lifetime for a switchgrass stand was set to 15 years.

A full summary of the lifetime reported in the reviewed literature is presented in Appendix 2.

Agricultural operations

Agricultural operations for the lifetime of the stand were derived from the literature and are presented in Table 2. They are converted into an yearly average inventory in a second time (p20). These agricultural steps are assumed for all stands with no regards to yield potential or irrigation requirement. Consequently, this part of the inventory is not spatialy explicit. In addition to scientific literature, reports issued by governmental agency (USDA, DEFRA, TEAGASC, NL agency) were used as they directly provide guidelines to farmers. The agricultural practices considered in this work can be seen as rather intensive when compared to other studies. Indeed, the establishment of a new crop on previously uncropped land is expected to be more challenging and to require additional steps and tools [84, 85]. In total, 28, 17 and 3 studies and reports detailing agricultural steps and farming practices were reviewed for miscanthus, switchgrass and reed canarygrass respectively (Table 2). Due to the limited information available on reed canarygrass, a farming scheme similar to the one of switchgrass is assumed. This assumption, as already been used for research purpose [61] and is supported existing similarities between the two crops. Indeed, both crops are established by seeds and can be harvested using conventional haying equipment [82, 86-88]. Finally, as further detailed page 17, harvesting periods and moisture content at harvest time are also similar.

Table 2: Life cycle field operations for growing and harvesting miscanthus, reed canarygrass and switchgrass biomass over the lifetime of the plantation.

Miscanthus	**Year 0**	**Year 1**	**Year 2**	**Year 3-17**
	Mowing[a] Weeding Ploughing	Lime application Harrowing - rotary (2) Cultivate Planting[b] Rolling Weeding (2) Topping[a] (Irrigation)	Weeding Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)	Weeding (2/15) Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)
	The farming cycle for the lifetime of the plantation was derived from [30, 43, 47, 50, 51, 53, 60, 62, 85, 89-101].			
Reed canarygrass	**Year 0**	**Year 1**	**Year 2**	**Year 3-10**
	Mowing[a] Weeding Ploughing	Lime application Harrowing - rotary (2) Cultivate Planting[b] Rolling (2) Weeding (2) Topping[a] (Irrigation)	Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)	Weeding (1/8) Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)
	The farming cycle for the lifetime of the plantation was derived from [21, 59, 60, 62, 81, 82, 84, 97, 99-108].			
Switchgrass	**Year 0**	**Year 1**	**Year 2**	**Year 3-15**
	Mowing[a] Weeding Ploughing	Lime application Harrowing - rotary (2) Cultivate Planting[b] Rolling(2) Weeding (2) Clipping[a] Topping[a] (Irrigation)	Weeding Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)	Weeding (2/13) Fertilizer application Cutting[c] Swathing Balling Bale loading (Irrigation)
	The farming cycle for the lifetime of the plantation was derived from [26, 30, 48, 108-118]. The farming cycle is also widely based on assumptions made for switchgrass.			

Values in brackets show the number of time an operation is repeated. Operations without specified values are carried out one time.
Operations in blue letters depend on the irrigation scenario considered. No irrigation is considered in a rainfed scenario while irrigation is considered every year starting from year one in an irrigated scenario.
Operations in brown letters refer to crop-specific processes.
[a] Mowing, topping and clipping with a rotary mower.
[b] planting using a potato planter for miscanthus and a seed drill for switchgrass and reed canarygrass
[c] Cutting and conditioning with a forage harvester for miscanthus; cutting only with a rotary mower for switchgrass and reed canarygrass

Land clearing

As the land is assumed to be abandoned, the first step of the cropping cycle is the removal of the existing vegetation. This is done by mowing the field with a rotary mower to ensure actively growing vegetation followed by the application of a broad spectrum herbicide with a field sprayer.

Field operations are assumed to start in the year before planting with the removal of the existing vegetation. Herbicide spraying before soil preparation is commonly recommended in the literature for both miscanthus [43, 51, 85, 91, 119] and switchgrass [81, 84].

Primary tillage

Following weed control, the field is inversed ploughed and left over winter so that frost activity can further break down the soil. This step can also efficiently control larvae's population, reducing the risk of insect damage during the establishment year [85]. Assumptions on the machinery used are presented in Table 11.

Ploughing is a necessary step for the establishment of miscanthus and was reported in all studies reviewed. Switchgrass at the contrary can be established under no-till management [81, 82, 84, 120, 121]. No till establishment of switchgrass is recommended in areas prone to erosion [102] and has shown good establishment results for a variety of climate and previous cropping systems [81]. No till methods preserve high soil moisture content and decrease fuel consumption and soil disturbance [122]. In the other hand, higher temperatures are achieved with conventional tillage which can favour seed germination [84]. Conventional tillage also has the advantage of reducing the amount of residue that could otherwise interfere with the seed drill [84, 123]. Large amounts of residue are expected following the removal of the previously established vegetation. In addition, based on the reviewed literature, conventional tillage appears to be the establishment method most commonly used in Europe with only one study reporting no-till establishment [101]. For these reasons, conventional tillage is considered for switchgrass and reed canarygrass.

Secondary tillage

Secondary tillage for the three crops includes two passes with a rotary harrow and one pass with a spring tine harrow (Table 11).

In the literature, the number of passes for secondary tillage ranges from one [26, 43, 104] to three [53, 81, 98] with most studies reporting two or three passes. As stated before, the soil preparation of former abandoned land is expected to require additional time and operation, therefore this work considers a total of three passes. For all three crops, rotary harrow and field cultivator were the most commonly used implements and often, both are used together [53, 60, 93, 107].

<u>*Planting*</u>

It is assumed that miscanthus is established via rhizomes while reed canarygrass and switchgrass are established via seeds. Miscanthus rhizomes are planted with a modified potato planter and a seed drill is used for switchgrass and reed canarygrass (Table 11). The field is rolled before planting for switchgrass and reed canarygrass and immediately after planting for all three crops.

Broadcast seeding of switchgrass and reed canarygrass has potential to reduce costs and energy consumption however, establishment success can be compromised on soil with heavy amounts of residues [44]. Thus, the use of a conventional seed drill is assumed in this work.

Miscanthus is most commonly propagated using rhizomes and plantlets [121, 124, 125]. The associated establishment cost is relatively high and remains one of the major obstacle to its large scale development [121, 124, 125]. While new propagation methods are being developed [51, 121], establishment via rhizome is considered in this work as it is cheapest, commercially available option today [51, 125]. The planting operation is assumed to be performed with a potato planter. A number of specialized machinery have been developed in the past years for rhizome planting [85] however, it is expected that farmers will use locally available machinery to minimize costs [95], motivating the choice of a potato planter in this work.

Rolling the field after planting improves soil contact with the rhizomes/seeds and has been shown to improve establishment success for all three crops [85, 94, 122]. In the case of switchgrass and reed canarygrass, a pre-planting rolling step to firm seedbed has also been effective in increasing establishment rates [84, 102]. Thus two rolling steps are considered for switchgrass and reed canarygrass while one rolling step is assumed for miscanthus.

Weed control

In addition to the weeding operation required ahead of soil preparation, a pre-emergence and a post emergence application of herbicide with a field sprayer (Table 11) are assumed during the first year for all three crops. For switchgrass, first year weed control is assumed to require an additional mowing operation, above crop canopy. During the second year, a pre-emergence application of herbicide is assumed for switchgrass and miscanthus only. Finally, between the end of the second year and stand renewal, two applications of herbicide are considered for miscanthus and switchgrass while one is considered for reed canarygrass. Occasional weeding operations during production years are assumed necessary to ensure long term productivity of the stand.

Weeds control is necessary throughout the lifetime of the crop to allow for maximum yields and stand persistence. Especially, seed bank reserves are expected to be relatively high on a land previously uncropped [94]. Weed competition during establishment has been identified as a major challenge and as one of the main cause of stand establishment failure for all three crops [79, 126, 127]. Indeed, while the planting process disturbs the soil and favors seed germination, seedlings of miscanthus, reed canarygrass and switchgrass show slow early growth under common spring temperature and compete badly with weeds [30, 79, 82]. However, following good establishment, perennial bioenergy grass stands are very competitive and the need for weed management is drastically reduced. Extensive information on weed management practice are available for miscanthus and switchgrass and the majority of sources considers weeding operation unnecessary past the end of the second year when the stand is well established [53, 128]. Information on weed management practices for reed canarygrass is scarce but the crop was shown to be more competitive than switchgrass [129] and herbicide use is not reported past the end of the first year [26, 108]. However, long term field trials show more contrasting results with occasional and stand specific requirement for weed control during production years [33, 78, 130-132]. For all three crops, reported weed management strategies are rather chemical (herbicide) rather than mechanical (hoeing) at the exception of switchgrass (clipping).

In line with the literature, intensive chemical weed management is considered until canopy closure. That is during the two first year for miscanthus and switchgrass and during the first year for reed canarygrass. An additional clipping operation, above switchgrass canopy is considered during the first year following [81, 106, 122]. Afterward, and in accordance with field trials observations, occasional applications of herbicide are assumed for older crops (Table 2, Table 5).

Harvest

In this work, biomass is assumed to be cut and balled once a year, from the second year on. During the first year, biomass is topped with a mower conditioner and left on the field. From the second year, miscanthus is cut with a forage harvester while switchgrass and reed canarygrass are cut with a rotary mower (Table 11). The implications of harvest timing are investigated through two different scenarios. An early harvest scenario, where biomass is harvested at peak standing yield and a late harvest scenario where biomass is left standing overwinter and harvested when fully senesced. While early harvest maximizes biomass, late harvest improves biomass quality. Due to biomass senescence, overwinter losses of 30%, 26% and 32% of peak standing biomass are assumed for miscanthus, reed canarygrass and switchgrass respectively. Delaying harvest is also assumed to decrease moisture content from 54%, 55% and 57% to 26%, 16% and 17% for miscanthus, reed canarygrass and switchgrass respectively (Table 4). Irrespective of the harvest timing, biomass is assumed to be cut and baled for all three crops. Additional field drying is assumed for all crops and all harvest regime except from early cut miscanthus. Thus a moisture content of 15% is assumed for balled biomass under a delayed harvest regime (Table 4). Under the early harvest scenario, balled miscanthus biomass is assumed to have a moisture content of 54% while balled reed canarygrass and switchgrass are assumed to have a moisture content of 20% (Table 4). For miscanthus, reed canarygrass and switchgrass respectively, it is assumed that 10%, 12% and 12% of the harvestable biomass is lost due to machinery inefficiency and stubble left on the field.

Biomass harvest is not considered during the first year. While it can improve economic return of a plantation [84], it can risk stand longevity [133]. Instead, biomass is topped [51, 53, 59, 89, 134, 135] to form a mulch and prevent weed growth [136].

In the following years, harvest time and frequency are determinant factors of biomass yield and quality, as well as stand longevity [87, 137]. While multiple cut systems have the potential to maximize biomass in the short term [138-140], detrimental effect were demonstrated on long term yield and stand longevity [137, 138, 141]. A single harvest system is assumed here as it is found to be best for bioenergy production [87, 105].

Biomass quality is also primarily determined by the time of harvest. Indeed, ash and moisture content generally decreases along the crop’s growing cycle [142-144]. Especially, during crop senescence, active nutrient translocation to belowground organs and passive nutrient loss through leaching and loss of crop tissue with high nutrient content (inflorescence, leaves), greatly improve biomass quality [42, 97, 145-147]. The loss of crop tissue during senescence constitute however a major drawback from delaying harvest as important yield loss can be observed due to harsh winter conditions and stand lodging [81, 97, 148, 149]. Thus, nutrient removal and fertilizer requirement will be higher for early harvest due to higher yield and biomass nutrient content. The importance of proper nutrient management for green harvest was stressed by (Strullu, Cadoux, 2011) as green harvest can also impair stand longevity by preventing full nutrient relocation, reducing stand vigour [49, 137]. The intended final use of the biomass is decisive in the choice of a harvest system as it will determine biomass quality requirements and the economic feasibility of fertilizer use [49, 84, 105].

In Europe a consensus exists that miscanthus biomass can be harvested either in autumn, shortly after the end of the growing season or following winter without risks for stand longevity [141, 150]. For switchgrass, diverse opinion exits and recommendation vary from harvest at peak standing biomass [151] to harvest following winter [45, 130] with other studies recommending harvest after killing frost [45, 120, 151]. Finally, reed canarygrass is most often used for combustion and thus harvested in spring [30, 79, 152]. Indeed, early harvested biomass is considered inappropriate for combustion purposes due to the low heating value and high risk of slagging [144, 145]. At the contrary, early harvested biomass is preferred for biogas and bioethanol production [86, 141, 153, 154]. This work does not assume a specific end use pathway for the produced biomass. However as explained in this sections, market opportunities exist that could support the full range of harvest time. This work compares for all three crops the two extreme scenarios of an early harvest at peak biomass with a delayed harvest following winter. It is assumed that harvest time has no influence on stand longevity.

The timing for early harvest depends on the growing cycle of each crop, climate and variety choice [87]. In Europe, miscanthus generally reaches peak biomass in late fall [144, 148]. Reed canarygrass and switchgrass however have a shorter growing cycle and peak biomass can be reached between late summer [41, 155, 156] and fall [41, 157, 158]. Delayed harvest timing coincide for all three crops and ranges from late winter [147, 159, 160] to early spring [159, 161, 162] before emergence of new shoots [97]. In line with those observations, large differences in harvest timing are expected across Europe. Nevertheless, this work assumes that peak yields will generally be achieved earlier in the season for switchgrass and reed canarygrass than for miscanthus.

Losses from delaying harvest were estimated from field experiments and are assumed to be 30%, 26% and 32% of peak biomass yield for miscanthus, reed canarygrass and switchgrass respectively (detail in Appendix 4, Appendix 6 and Appendix 8). Biomass loss are assumed to entirely contribute to litter formation. Degradation through microbial activity is expected to have a negligible contribution to biomass losses and will not be considered in this work due to the lack of available information [41].

Harvest timing is an important parameter to consider as it determines the feasibility of field drying between cutting and baling operations. Studies have demonstrated the feasibility of field drying for switchgrass and reed canarygrass harvested in autumn with reduction of the moisture content from 66.2% to 22.6% [163]. Field drying is not considered for early harvested miscanthus as no source could be found to support this assumption. Irrespective of the crop, delayed harvest is assumed to happen as soon as climatic conditions allow for field drying. Biomass moisture content at cutting time were derived from the literature and are presented in Table 4 (detail in Appendix 9, Appendix 10 and Appendix 11). For reed canarygrass and switchgrass harvested at peak biomass, moisture content was assumed to be 20% after field drying, following observations from field trial [88, 163, 164]. For all three crops under a delayed harvest scenario, a moisture content of 15% was assumed, in line with values reported in [79, 85, 86, 88, 165-169].

Harvest loss were estimated from the literature. For miscanthus, reported harvest loss for a cutting balling system range from 5% [89] to 16% [170]. An intermediate value was assumed in agreement with [171]. Switchgrass harvest loss were estimated based on (Cherney, Paddock, 2013) assuming stubble height of 10cm. Stubble height was assumed following [128, 143, 158, 173]. Assumed harvest loss for switchgrass are in line with values reported elsewhere [174]. Harvest loss for reed canarygrass were assumed to be equal to harvest loss for switchgrass. Indeed, information on reed canarygrass is scarce and often the distinction between pre-harvest loss and harvest loss is not explicit [175, 176]. Values seem realistic when compared to field observations reported by (Hadders and Olsson, 1997).

Fertilizer application

Fertilizer application with a broadcaster is assumed every year from the second year on.

Fertilizer application is not considered during the first year because it has been shown to promote weed growth without substantial benefits for the crop [84, 177]. Indeed, miscanthus, switchgrass and reed canarygrass seedlings are good nutrient scavengers and soil reserves are expected to provide sufficient amounts of nutrients [85, 178]. Application of fertilizer during the first year generally increases weed competition, establishment cost and economic risk [84]. From the second year on and to prevent soil depletion nitrogen, phosphorus and potassium are applied one time a year with a tractor mounted broadcaster [177, 179].

Irrigation

Under irrigated conditions, irrigation is assumed to start on the year of establishment. Indeed, seedlings are found to be the most sensitive to water stress [81, 85].

Agricultural operation for one hectare during one year.

The total number of operation over the lifetime of the stand are discounted by the number of years to obtain yearly operation requirements that account for the entire life cycle of the stand (Table 3). This section of the inventory is not spatial explicit and will be considered for all cropped area in Europe.

Table 3: Average yearly agricultural operation for one hectare of land cultivated for bioenergy production

	Miscanthus	**Reed canarygrass**	**Switchgrass**
	17 years	**10 years**	**15 years**
Mowing	0.06	0.10	0.07
Weeding	0.35	0.40	0.40
Ploughing	0.06	0.10	0.07
Lime application	0.06	0.10	0.07
Harrowing	0.12	0.20	0.13
Cultivate	0.06	0.10	0.07
Planting	0.06	0.10	0.07
Rolling	0.06	0.20	0.13
Clipping	-	-	0.07
Topping	0.06	0.10	0.07
Fertilizer application	0.94	0.90	0.93
Cutting	0.94	0.90	0.93
Swathing	0.94	0.90	0.93
Balling	0.94	0.90	0.93
Bale loading	0.94	0.90	0.93
Irrigation	(1)	(1)	(1)

Values in blue depend on the irrigation scenario considered.
- Indicates that the process is not considered for the crop

Agricultural inputs

Agricultural inputs were quantified from the literature and are presented in a first place for the entire lifetime of the crop. This work assumes a relationship between some of the inputs (fertilizer use, diesel consumption, irrigation water) and spatial variables (irrigation requirement, yield). Thus, part of the inventory described in this section is spatially variable. As for the agricultural operations, reports issued by governmental agency (USDA, DEFRA, TEAGASC, NL agency) were used. Input values considered in this work (herbicides, planting density) might be regarded as high but are considered realistic under the assumed high input management system. Assumptions for reed canarygrass are once again often based on the assumptions for switchgrass.

Planting density

Miscanthus is established at a density of 17000 rhizomes per hectares. Switchgrass and reed canarygrass are established at seeding rates of 10 and 20 $kg.ha^{-1}$ respectively. While other studies consider patch-planting during the second year [106, 180] this work assumes sufficient establishment during the first year and patch planting is not considered.

Reported planting density for miscanthus range from 10000 to 40000 rhizomes per hectares [89, 101] with most reported values ranging from 15000 and 20000 rhizomes per hectares. An intermediate planting density of 17000 rhizomes per hectares is considered here. Indeed, higher planting densities increase establishment cost without long term yield benefits [181].

Switchgrass seeding rates vary across the literature from 5.6 to 20 $kg.ha^{-1}$ [104, 106]. Values are inconsistently reported either in kilogrammes or in kilogrammes of Pure live seeds (PLS) making difficult comparison between studies. The absolute (not as PLS) rate of 10 $kg.ha^{-1}$ was estimated based on [30, 33, 82, 122].

For reed canarygrass, reported value range from 7.5 to 26 [111, 118]. If cultivated for energy use, (Ustak, Šinko, 2019) and (Santibañez, Urrutia, 2018) recommended seeding rates of 20 to 25 $kg.ha^{-1}$ and 15 to 20 $kg.ha^{-1}$, respectively. In agreement with the reviewed sources, a seeding rate of 20 $kg.ha^{-1}$ was chosen.

N, P, K Fertilizer

This work assumes nitrogen, phosphorus and potassium fertilizer application rates equal to nutrient removal in the harvested biomass. Yearly nutrient removals are computed as the product of the yearly harvested yield and the nutrient content of the harvested biomass (equation 1) and are therefore site-specific. Biomass nutrient content were derived from the literature and are presented in Table 4. Nutrient concentration is considered constant across irrigation scenarios but varies for different harvest time. Nutrient requirements are assumed constant across stand age. N, P and K are applied as urea, diammonium phosphate and potassium chloride respectively. The assumed nitrogen content of urea is 46%.

Table 4: Above ground biomass composition at harvest time

	Miscanthus		**Reed canarygrass**		**Switchgrass**	
	Early	Late	Early	Late	Early	Late
Moisture content (%)	54 (54)	26 (15)	55 (20)	16 (15)	57 (20)	17 (15)
N content (%)	0.52	0.30	1.0	0.71	0.77	0.35
P content (%)	0.10	0.058	0.16	0.097	0.17	0.045
K content (%)	0.97	0.55	1.0	0.19	0.57	0.10

Nutrient content were derived from the reviewed literature: [49, 59, 109, 141, 147, 148, 159, 170, 177, 182-187] for miscanthus, [36, 46, 48, 112, 117, 131, 155, 157, 160, 162, 188-192] for reed canarygrass and [33, 128, 130, 143, 156, 158-160, 193-197] for switchgrass. Details are provided in ***Appendix 12****,* ***Appendix 13****,* ***Appendix 14****,* ***Appendix 15****,* ***Appendix 16*** *and* ***Appendix 17****.*

Moisture content were derived from the reviewed literature: [47, 49, 97, 137, 141, 148, 159, 161, 198-200] for miscanthus, [46, 88, 155, 160, 162, 163, 190] for reed canarygrass and [88, 97, 128, 137, 143, 156, 158-160, 163, 168, 173, 201] for switchgrass. Details are provided in ***Appendix 9****,* ***Appendix 10*** *and* ***Appendix 11****.*

Moisture content are given for the cutting operation while values in brackets correspond to moisture content at the time of balling. Field drying only is assumed between cutting and balling. Field drying is not considered for early harvested miscanthus.

The yield response to fertilizer application has been extensively studies for all three crops and have shown contrasting results [41, 130, 177, 202]. As for now, fertilizer requirement are not yet fully understood [32, 203] but it is clear that local environmental factors such as soil nutrient availability and nitrogen deposition rates are major influencing factors [204, 205]. The general consensus seen in the literature is that all three crops show a null or positive general response to fertilization [41, 177, 203, 206, 207]. Thus, fertilizer use and especially nitrogen fertilizer use will generally be required to reach competitive yields [203, 208]. In turn, environmental performances will usually worsen and farming costs increase [203, 209]. In addition, although perennial grasses have high nutrient absorption and nutrient use efficiency, continuous harvesting of large amounts of biomass could nevertheless deplete soil nutrient stocks and threaten long term productivity of the stand [147, 159, 203, 204]. Hence adequate fertilizer management appears to be a key issue for bioenergy production.

This work assumes a high input agricultural system that uses optimum amounts of fertilizer. Applying fertilizer to match nutrient uptake has been proposed for miscanthus [85, 177] and switchgrass [45, 82, 84, 122] and used in several studies already [60, 180, 210]. Following those recommendations, the fertilizer application rate for nutrient i ($Input_i$) is assumed equal to the nutrient removal from harvest. It is computed following equation 1 from the harvested yield ($yield_{harvested}$) and the content of the harvested biomass in nutrient i ($[i]_{harvested\ biomass}$)

$$\mathrm{Input_i} = \mathrm{yield_{harvested}} * [i]_{harvested\ biomass} \qquad 1$$

$i \in [N, P, K]$
$Input_i$ in kg $N.ha^{-1}$, kg $P.ha^{-1}$, kg $K.ha^{-1}$ for N, P and K respectively

This approach allows to account for the spatial relationship between fertilizer application rates and local biomass yield potential. Indeed, biomass yield cannot indefinitely increase in all location with increased fertilizer application. Following this method, site-specific fertilizer requirement can be obtained from GAEZ yield estimates and location with lower yield potential will receive proportionally lower fertilizer inputs. The rational for this approach is to prevent unsustainable soil mining of nutrients. In addition, this method is consistent with the assumption that no fertilizer is applied during the establishment year. This work does not attempt to guarantee nutrients mass balance at the field scale. Input sources such as nitrogen deposition and output such as leaching, volatilization and runoff are not considered for the quantification of fertilizer requirement. Application rates might be regarded as low when compared to other studies and recommendation [81, 109, 211]. However as explained before, GAEZ high input scenario considered optimum amounts of fertilizer which might be considerably different from the highest application rates. Besides, perennial grasses have extensive root systems and are excellent scavengers of nutrients [84, 177, 212] and several studies have reported nutrient removal superior to fertilizer application rates [120, 212]. In addition, excessive fertilizer application was shown to promote lodging and weed competition which in turns reduces harvestable biomass [120, 203, 213, 214]. Evidences exist that the recovered fraction of applied fertilizer depends on local climate and water availability. [187, 203, 215]. Such effects are not modelled in this work and differences in fertilizer consumption between scenarios can entirely be explained by variations in harvested yield and variations in nutrient concentration.

Average crop nutrient concentration were derived from the literature (Appendix 12, Appendix 13, Appendix 14, Appendix 15, Appendix 16 and Appendix 17). Luxury consumption of nutrient has been shown for all three crops under fertilized treatment [33, 131, 147, 187]. However, nutrient contents were collected from the literature irrespectively of the fertilization treatment. The effect of stand age on biomass nutrient content was not included and observations from stand older than one year were all considered. As explained earlier, large differences in nutrient concentration exist between harvest time. Biomass harvested at peak biomass has a higher nutrient content than senesced biomass. For this reason, fertilizer requirement per tonne of harvested biomass are higher for peak harvest than for delayed harvest. Absolute fertilizer use will decrease further more in a delayed harvest system due to the reduction in biomass yield.

Nitrogen fertilizer is assumed to be applied as urea following recommendation from (Monti, Zegada-Lizarazu, 2019). The authors found urea to be the most effective and the most economically viable fertilizer option. Potassium is assumed to be applied as potassium chloride and phosphorus is assumed to be applied as diammonium phosphate.

Lime use

Lime requirement are assumed to be 175 $kg.ha^{-1}.yr^{-1}$ applied at once, during soil preparation. That is 2975, 1750 and 2625 kg of lime for miscanthus, reed canarygrass and switchgrass respectively.

Lime is used in agriculture to remedy soil acidification. While various processes are involved in agricultural soil acidification, the main causes today are ammonium fertilizer and urea application [216]. Evidence exist that switchgrass is sensitive to soil acidification [203]. More generally, all three crops grow best under certain pH conditions (Table 1) which yearly application of urea could disrupt. To ensure adequate soil pH during the lifetime of the stand this work assumes lime application during soil preparation. Lime application rates are based on (Hamelin, Jørgensen, 2012), (Bullard and Metcafe, 2001) and (Styles and Jones, 2007). (Hamelin, Jørgensen, 2012) reported average yearly application rates of 167 $kg.ha^{-1}$ pure calcium carbonate on Danish agricultural land. (Styles and Jones, 2007) reported similar yearly application rates on average in Ireland (170 $kg.ha^{-1}$). Finally, (Bullard and Metcafe, 2001) assumed yearly application rates of 187.5 $kg.ha^{-1}$ in the United Kingdom. An intermediate value of 175 $kg.ha^{-1}.yr^{-1}$ was assumed in line with the literature. This assumption is below the application rate reported from reed canarygrass field experiments by (Mäkinen, Soimakallio,

2006) (800 kg.ha^{-1}.yr.$^{-1}$) but is above the assumption from (Rettenmaier, Gärtner, 2015) who assumed application rate of 44 kg.ha^{-1}.yr.$^{-1}$ in a Mediterranean environment. National scale averages were preferred over single field experiment or single study assumptions as lime application rate depends on site-specific soil conditions.

Pesticide

Very few pests other than weeds have been identified as potential threat to the three crops. Thus, the only pesticides considered in this work are herbicides. The occurrence of herbicide application has been described in a previous section (p16). Assumptions on chemical product and application rates are presented in Table 5. This work considers the herbicides most often mentioned in the literature. Product-specific standard application rates are assumed in this work. Herbicides are assumed to be applied with 500l of water to obtain good coverage.

Table 5: Herbicide application rates

		Miscanthus	**Reed canarygrass**	**Switchgrass**
Year 0		Glyphosate (1.8)	Glyphosate (1.8)	Glyphosate (1.8)
Year 1	**Pre-emergence**	Pendimethaline (1.6)	Glyphosate (1.4)	Glyphosate (1.4)
	Post-emergence	Mecoprop-P (1.5) Bromoxynil (0.28) Ioxynil (0.28)	2.4-D (0.76) Dicamba (0.28) Nicosulfuron (0.02)	2.4-D (0.76) Dicamba (0.28) Nicosulfuron (0.02)
Year 2	**Pre-emergence**	Dicamba (0.3)		2.4-D (0.76) Dicamba (0.28) Nicosulfuron (0.02)
Maintenance years	**Pre-emergence**	Glyphosate (1.4)	Glyphosate (1.4)	Glyphosate (1.4)
	Post-emergence	Dicamba (0.3)		2.4-D (0.76) Dicamba (0.28) Nicosulfuron (0.02)

Values in bracket correspond to the application rate in kilogram of active ingredient (a.i)
Herbicide use and application rate were derived from the literature: [33, 43, 50, 51, 53, 78, 85, 93, 98, 134] for miscanthus, [33, 81, 84, 104, 108, 128, 130, 159, 173, 195, 217]

Herbicide application rates over the lifetime of a stand are dependent on field location, previous cropping history, seed reserves and product used. Therefore, values reported from field experiments show large variations. For miscanthus application rates vary from 105g of active ingredient (ai) per hectares [50] to 14.13 kg ai.ha^{-1} [78]. For switchgrass application rates vary from 654g ai.ha^{-1} [159] to 17.56 kg ai.ha^{-1}. For reed canarygrass, information is scarce and the only study reporting application rate (2.3l.ha^{-1}) [108]. Differences between reported values can mainly be explained by differences in stand lifetime, product used and number of application.

Indeed, rather standard application rates are used during weed control operations to ensure effective weed control without crop injury.

Controlling the existing vegetation before planting is a required step for all three crops. Little information was found and assumptions are based on agricultural practices used for miscanthus. Glyphosate is commonly used in Europe for this operation [51]. Application rates were taken from (Murphy, Devlin, 2013), (Caslin, Finnan, 2015), (Moritz, Andreas, 2017)

Regarding miscanthus, pendimethaline is sprayed before emergence of the crop during the first year to control annual grasses and certain broadleaf weeds. A post emergence application of mecoprop-P, bromoxynil and ioxynil is then used to control broadleaf weeds regrowth. During the second year, a pre-emergence application of dicamba is assumed for controlling remaining broadleaf weeds before seedling emergence. In the following years, only two more applications of herbicide are considered. One to control grassy weeds (glyphosate) and one to control broadleaf weeds (dicamba). Application rates were taken from (Murphy, Devlin, 2013), (Morandi, Perrin, 2016), (Christian, Riche, 2008), (Caslin, Finnan, 2015), (Moritz, Andreas, 2017) and compared to maximum application rates reported in (Anderson, Arundale, 2011).

For switchgrass, most studies report the use of atrazine or quinclorac which are banned in Europe [48, 81, 84, 108, 195]. A pre-emergence application of glyphosate is considered during the first year following [81, 84]. A mix of 2.4-D, dicamba and nicosulfuron is then applied to control broadleaf weeds when seedling have already emerged [30, 128, 159, 217-219]. During the second year, pre-emergence control of broadleaf weed is performed using the same mix of 2.4-D, dicamba and nicosulfuron. Two other applications are assumed in the following years to control grassy weeds (glyphosate) and one to control broadleaf weeds (2.4-D, dicamba and nicosulfuron).

Herbicide use for reed canarygrass is based on the assumptions made for switchgrass. Weed control is however not believed to be a problem past the first year and due to the shorter lifetime of the crop, only one application of glyphosate is assumed during the maintenance years.

Other pesticides are not considered because no severe disease or pest has yet been identified for any of the three crops in Europe [60]. In addition, no economically viable treatment has yet been found for any of the identified diseases [30, 81] and planting resistant variety is often the recommended approach [81].

Pesticides are applied with 500l of water following recommendation from (Caslin, Finnan, 2015)

<u>Fuel consumption:</u>

Fuel consumption were collected from the literature. Values for harvesting and planting operations were taken from crop-specific literature as crop is assumed to affect field efficiency and fuel consumption. For other operations, fuel consumptions were primarily taken from large scale studies and national reports. For the cutting operation, diesel consumption is assumed proportional to the harvest dry matter yield (unit: $l.tDM^{-1}$). For the balling and loading operation, fuel consumption is assumed proportional to the number of bales (unit: $l.bale^{-1}$). For irrigation, energy consumption is assumed proportional to the amounts of irrigated water (unit: $l.m^{-3}$). Finally, for other operations, fuel consumption is independent on the yield and depends on the area only (unit: $l.ha^{-1}$). Assumptions are presented in Table 11.

Detail about the collected values are presented in Appendix 20, Appendix 21, Appendix 22 and Appendix 23. A general observation for the cutting operation is that fuel consumption per unit area generally increases with yield [204]. However, the increase is not necessarily linear [204]. In this work the fuel consumption for cutting was nevertheless assumed to be proportional to the dry harvested biomass. Contrary, the fuel consumption for balling was assumed proportional to the number of bales which is determined by the wet harvested biomass. In the literature fuel consumption values are either reported per unit area, or per unit mass harvested. Both values were collected and fuel consumption per unit area were converted in fuel consumption per unit dry mass harvested by dividing with the associated yield. The average value across study was then selected for this work. For balling, the average fuel consumption per unit dry matter harvested were found to be 1.22 $l.tDM^{-1}$ for miscanthus and 1.13 $l.tDM^{-1}$ for switchgrass and reed canarygrass. Values were then converted into fuel consumption per unit fresh weight harvested assuming 15% moisture content as this was the value most commonly reported in the literature [88, 163, 166-168]. For miscanthus assuming 15% moisture content, the fuel consumption per unit fresh weight was found to be 1.04 $l.tFW^{-1}$ while for switchgrass and reed canarygrass it was found to be 0.961 $l.tFW^{-1}$. Assuming a bale fresh weight of 200 kg [220], the fuel consumption per bale were found to be 0.21 and 0.19 $l.bale^{-1}$. Differences between miscanthus and the two other crops seem reasonable with regards to the thickness of the stem of miscanthus that requires additional power to be broken and compacted. Final assumptions are presented in Table 11.

Water for irrigation:

Site-specific yearly water requirement for irrigation were obtained from GAEZ. Values are equal to the water deficit estimated by the model during the growing cycle of the crop.

Yearly input requirement

Total input for the lifetime of the stand are discounted by the number of years to obtain yearly life cycle input (Table 6). Input that depend on yields (fuel consumption for harvesting operation, fertilizer requirement…) and irrigation are treated differently. Indeed, yield estimates from GAEZ are average maximum biomass yield over the lifetime of the crop. Thus, GAEZ yields already accounts for the absence of harvest during the first year. Similarly, GAEZ already provides yearly irrigation water requirement.

Table 6: Average yearly input requirement for one hectare of land cultivated for bioenergy production

		Miscanthus	Reed canarygrass	Switchgrass
	unit	17 years	10 years	15 years
Water - pesticide	(m^3)	0.18	0.20	0.20
Water - irrigation	(m^3)	*	*	*
Rhizomes / seeds	(p)/(kg)	1000	2	0.67
Lime	(kg)	175	175	175
Glyphosate	(g ai)	191	468	312
Pendimethaline	(g ai)	94	-	-
Mecoprop-P	(g ai)	88	-	-
Bromoxynil	(g ai)	17	-	-
Ioxynil	(g ai)	17	-	-
Dicamba	(g ai)	35	28	37
2.4-D	(g ai)	-	77	153
Nicosulfuron	(g ai)	-	2	3
Diesel - cutting	(l)	‡	‡	‡
Diesel - baling	(l)	‡	‡	‡
Diesel - bale loading	(l)	‡	‡	‡
Diesel - irrigation	(l)	†	†	†
Diesel - field operation⁑	(l)	⁋	⁋	⁋

- Indicates that the crop is not considered by the input.
** Site-specific irrigation volumes are obtained from GAEZ. GAEZ provides yearly values and data are used as they are.*
‡ Diesel consumption for the cutting, balling and bale loading operation is yield-dependent and site specific.
† Diesel consumption for irrigation depends on the irrigation volumes and is site-specific.
⁑ Here, field operation encompasses all operations that are not depending on the yield or the irrigation volumes. That is all the operations performed during the establishment of the crop plus the weeding operations during maintenance years. Those operations are constant for all stands, regardless of the yield, and irrigation scenarios.
⁋ Fuel consumption from field operations can easily be computed from Table 4 and Table 11. However, in this work, fuel consumptions are modelled as inputs to the different agricultural steps. Thus, yearly fuel consumption is modelled through the use of the different agricultural processes but never explicitly.

Agricultural outputs and residue production

This section presents the different agricultural outputs quantified for this system. Agricultural outputs describe here the different flows arising from biomass production and comprises biomass yield and the associated number of bales as well as all types of residues. Quantifying the amount of biomass harvested is important to model a certain number of inputs (fertilizer requirements, fuel consumption from harvesting and balling operations) but also to assess the overall efficiency of crop cultivation. Quantifying the production and the composition of different residues in the other hand, is important for modelling biogenic emissions. All flows quantified in this section are yield dependant and therefore site-specific.

Biomass yield and number of bales:

As previously mentioned, yield estimates from GAEZ are assumed to be average yields over the lifetime of the stand, already accounting for the absence of harvest during the first year. Thus, site-specific yearly harvested biomass yield ($yield_{harvested}$) are obtained from GAEZ estimates ($yield_{GAEZ}$) and in the case of a delayed harvest, winter losses ($loss_{winter}$), as detailed in equation 2. Indeed, biomass yields obtained from GAEZ are post-harvest maximum yields [221] which correspond to the early harvest scenario. For a delayed harvest, the estimated GAEZ yield is reduced by 30%, 26% and 32% for miscanthus, reed canarygrass and switchgrass respectively, in agreement with the assumption on winter losses. The number of bale in computed following equation 3 from the harvested yield ($yield_{harvested}$), the moisture content at baling time ($moisture_{balling}$) and the bale weight ($weight_{bale}$). Bales are assumed to weight 200kg in line with [220].

$$\text{yield}_{\text{harvested}} = \begin{cases} \text{yield}_{\text{GAEZ}} & \text{harvest =early} \\ \text{yield}_{\text{GAEZ}}\ (1 - \text{loss}_{\text{winter}}) & \text{harvest =late} \end{cases} \tag{2}$$

$$\text{number of bale} = \frac{\text{yield}_{\text{harvested}}}{((1 - \text{moisture}_{\text{balling}}) * \text{weight}_{\text{bale}})} \tag{3}$$

Aboveground residues from harvest

As mentioned in a previous section (p 17), 10%, 12% and 12% of the standing biomass is assumed to be lost due to machinery inefficiencies and stubble left on the field for miscanthus, reed canarygrass and switchgrass, respectively. However, GAEZ estimates are post-harvest maximum yields and are therefore different from peak standing biomass. Peak standing biomass is obtained from GAEZ yields ($yield_{GAEZ}$) and harvest loss estimates ($loss_{harvest}$) following equation 4. Depending on the harvest scenario, the biomass standing before harvest is then obtained from equation 5. Absolute harvest losses are then obtained as the difference between the standing biomass before harvest and the harvested biomass (equation *6*). Residue from harvest are assumed to have a similar composition than the harvested biomass. For miscanthus, reed canarygrass and switchgrass respectively, that is a nitrogen content of 0.52%, 1%, 0.77% for residues from early harvest and 0.30%, 0.71%, 0.35% for residue from a delayed harvest (Table 4)

$$yield_{peak} = \frac{yield_{GAEZ}}{(1 - loss_{harvest})} \qquad 4$$

$$yield_{standing} = \frac{yield_{harvested}}{(1 - loss_{harvest})} = \begin{cases} yield_{peak} & \text{harvest=early} \\ yield_{peak}(1 - loss_{winter}) & \text{harvest= late} \end{cases} \qquad 5$$

$$residue_{harvest} = yield_{standing} - yield_{harvested} \qquad 6$$

Aboveground and belowground residues from senescence

Belowground residue from biomass senescence are not quantified in this work. Indeed, no consistent estimate of the amount and fate of belowground residue produced yearly could be found. Aboveground residue production from senescence of biomass was however quantified as already developed in a previous section (p17). Absolute residue production is calculated following equation 7. Senesced residues are assumed to have a nitrogen content of 0.39%, 0.83%, 0.49% for miscanthus reed canarygrass and switchgrass (Table 7).

$$residue_{senesced} = \begin{cases} 0 & \text{harvest=early} \\ yield_{peak} - yield_{harvested} - residue_{harvest} & \text{harvest=late} \end{cases} \qquad 7$$

Few studies were found that investigated belowground biomass dynamics for miscanthus and none were found for switchgrass and reed canarygrass. In general, belowground biomass dynamics are poorly understood and it remains very difficult to quantify root and rhizome recycling into soil [186]. Observations reported for miscanthus show large variations. [186]

reported that necrotic rhizomes after 3 years accounted for estimates 1.1 to 2.9% of total belowground biomass. (Kahle, Beuch, 2001) reported similar observations from stands up to 6 years old. However, (Mun, 1988) et al reported that 25% of m. sinensis belowground biomass dies of annually. (Clifton-Brown, Breuer, 2007) reported intermediate value with dead rhizome accounting for 19% of the total rhizome biomass after 11 years. Due to the reduced number of observations and to the difficulty to compare reported results (differences in stand age, difference in the fraction of belowground biomass considered…) no trend could be found it was decided to exclude yearly belowground residues from the analysis.

Aboveground residue from senescence are considered for delayed harvest as detailed in a previous section (p17). The nitrogen content of senesced residues was estimated from the literature. For miscanthus, a nitrogen content of 0.39% is assumed following field measurement [147, 186]. This value is lower than the nitrogen content of the whole plant at peak harvest, which is expected as the litter is formed by the fall of dead material [89]. However, senesced residues are primarily composed of dead leafs and inflorescence which tend to have higher nitrogen content than the stem [200, 223]. It is therefore considered reasonable that the nitrogen content of the litter is assumed higher than the nitrogen content of the standing biomass following senescence. For reed canarygrass and switchgrass, no study could be found that looked at the composition of the litter layer. In agreement with the observation made for miscanthus, an intermediate nitrogen content was assumed for the two crops (Table 7). The litter layer was assumed to have the same nutrient content than the one of the all crop harvested following a killing frost (Appendix 18, Appendix 19).

Table 7: Senesced residue composition

	Miscanthus	Reed canarygrass	Switchgrass
N content (%)	0.49	0.83	0.49

Nutrient content were derived from the reviewed literature: [147, 186] for miscanthus, [36, 109, 189] for reed canarygrass and [32, 104, 130, 143, 160, 193-195, 197, 205, 224, 225] for switchgrass. Details are provided in Appendix 18 *and* Appendix 19.

Above and belowground residues from renewal

This work assumes a steady state system where stands are renewed at the end of the cropping cycle. During stand renewal large amounts of belowground residues are produced as the entire belowground biomass dies. Belowground biomass is estimated from the peak standing biomass using a root to shoot ratio of 0.8. Belowground residue production is discounted over the entire lifetime of the stand and given by equation 8. It is assumed that the harvest timing has no influence on the root biomass. No aboveground residues from renewal are considered in this work as biomass is assumed to be harvested in the last year of the stand's cycle. Belowground residues are assumed to have a nitrogen content of 1%, 1%, 0.9% for miscanthus reed canarygrass and switchgrass ().

$$residue_{belowground} = \frac{yield_{peak} * ratio_{belowground}}{cycle} \quad (8)$$

The amount of belowground biomass at the end of the cycle is estimated using a root to shoot ratio of 0.8 for all three crops following recommendation from the IPCC [226]. For miscanthus, root to shoot ratio estimates vary from 0.35 [180] to 1 [186]. Reported estimates for switchgrass compare better with the default factor from the IPCC and vary from 0.8 in October [84] to 1.3 [174], with (Wilson, Heaton, 2013) reporting a shoot to root ration of roughly 0.7. Finally, two studies were found reporting shoot to root ratio for reed canarygrass and values ranged from 1 [227] to 0.54 [228]. The IPCC default factor was selected as it was within the range of reported value for every crop. Evidence exist that harvest timing influences belowground biomass dynamic [212]. However, this work assumes equal belowground biomass for early and delayed harvest.

The nitrogen content of miscanthus belowground residues was assumed to be 1% following observations from (Kahle, Beuch, 2001), (Amougou, Bertrand, 2011) and in line with assumptions from (Hamelin, Jørgensen, 2012) . For reed canarygrass, a nitrogen content of 1% is also assumed following observations from (Xiong, Landström, 2009), (Bernard and Lauve, 1995). Finally, for switchgrass, a lower nitrogen content is assumed based on observations from (Wayman, Bowden, 2014), (Giannoulis and Danalatos, 2014), (Heggenstaller, Moore, 2009) and (Wilson, Heaton, 2013) (Table 8) .

Table 8: Belowground residue composition

	Miscanthus	**Reed canarygrass**	**Switchgrass**
N content (%)	1	1	0.9

Nutrient content were derived from the reviewed literature: [170, 186] for miscanthus, [227, 229] for reed canarygrass and [174, 215, 230] for switchgrass.

Emissions to air and water

This section details assumptions related to emissions to air and water arising from the cultivation of perennial crops. Emission to air include gases (ammonia, nitrogen oxides, CO2, nitrous oxides, NMVOCs) and particulate matter (PM2.5, PM10, TSP). Emission to water include emissions of phosphorus and nitrogen through leaching and runoff. Emissions from diesel burnt in agricultural machinery are treated separately (p 39). A complete summary of the factors used for modelling emission is presented in Appendix 24. Part of the inventory described in this section depends on site-specific yield.

Emissions from pesticide application

All pesticides applied are accounted as emissions to soil [220]. Emissions to air from pesticide use are not accounted for, following recommendation from (Hutchings and Barbara Amon, 2019).

CO2 from liming and urea application

CO_2 emission from lime application and urea fertilizer use were modelled following the IPCC methodology [232]. The respective emission factor for lime and urea application are assumed to be 0.44 $kg_{CO2}.kg_{lime}^{-1}$ and 0.73 $kg_{CO2}.kg_{urea}^{-1}$. Assuming a nitrogen content in urea of 46%, the emission factor for urea is also equivalent to 1.59 $kg_{CO2}.kg_{N\ applied}^{-1}$.

NMVOC, PM10, PM2.5, TSP

Particulate and NMVOC emission from stand cultivation are considered in this work following recommendation from (Hutchings and Barbara Amon, 2019). Yearly emission factors for NMVOC, PM2.5, PM10 and TSP are assumed to be 0.86, 0.06, 1.56 and 1.56 $kg.ha^{-1}.yr^{-1}$ respectively [231].

Nitrogen oxides

It is assumed that 1.1% of applied N is emitted as NO_x-N following urea-specific emission factor reported in (Hergoualc'h, Akiyama, 2019). Emission from senesced and harvest residues are not considered as no method currently exists [231]. The emission factor for nitrogen oxides is considered constant across crops, irrigation scenario and harvest scenario. The emission factor assumed here correspond to 0.037 kg of nitrogen dioxide emitted per kilogram of nitrogen applied under the form of urea. Following the assumption that nitrogen fertilizer application depends on local yield, nitrogen oxides emissions are also site-specific.

Ammonia

It is assumed that 14.2% of applied N is emitted as NH_3-N following urea-specific emission factor reported in (Hergoualc'h, Akiyama, 2019). Emission of ammonia from senesced residues, harvest residues and crop foliage are not considered in agreement with (Hutchings and Barbara Amon, 2019). The emission factor for ammonia is considered constant across crops, irrigation scenario and harvest scenario. The emission factor assumed here correspond to 0.17 kg of ammonia emitted per kilogram of nitrogen applied under the form of urea. As for nitrogen oxides, ammonia emission from the cultivation of 1 ha of abandoned land will vary spatially.

In the last EMEP/EEA air pollutant inventory guidebook released in 2019, an emission factor of 4.1% of applied N is assumed for ammonia emissions under a standard tier 1 approach [231]. However, urea volatilization is estimated to range between 6 and 47% of applied N [231]. Therefore, a standard emission factor of 4.1% is believed to be unsuitable for proper modelling of ammonia emission from urea volatilization. In the refinement to the 2006 IPCC Guideline for National Greenhouse Gas Inventories, results from a metadata analysis reviewing 187 studies suggest an emission factor of 14.2% for urea [226]. This factor compares well with recommended tier 2 emission factor from EMEP/EEA guidelines [231]. Emissions of NH_3-N are converted to emission of NH_3 by multiplying with ${}^{17}/_{14}$.

Senesced residues are not believed to be sources of ammonia emissions [231]. Also, as no method currently exists, emissions from harvest residues and foliage are not considered [231].

Phosphorus leaching and runoff

Phosphorus leaching is estimated with the SALCA-P model [233] assuming yearly leaching of 0.18 kg PO_4^{3-} per hectares. Following the model, the value is constant across crops, fertilization level, irrigation scenarios and years. The same model is used for estimating phosphorus runoff. Runoff is assumed on all lands with no regard to the slope. Yearly runoff is computed as the sum a constant (0.77 kg PO_4^{3-} per hectare) and a variable term that depends on site-specific fertilizer use. The emission factor from fertilizer use is assumed to be 0.0044 kg PO_4^{3-} per kilogram of applied P, or 0.0019 kg PO_4^{3-} per kilogram P_2O_5 applied [233]. Phosphorus losses from drainage and soil erosion are not considered in this work. Emission factor for phosphorus leaching and runoff are assumed constant across Europe, harvest timing

and irrigation scenario. Absolute runoff will however vary with fertilizer application and thus, with the yield.

In the absence of slurry application, the SALCA-P model estimates yearly phosphorus leaching based on a constant emission factor of 0.18 kg PO_4^{3-} per hectare for pasture and meadow land and a factor of 0.22 PO_4^{3-} per hectare for arable land. This study focuses on perennial grasses with deep rooting system that have shown reduced nutrient leaching when compared to arable land [52, 234, 235]. Thus, the emission factor applied in this study is the one of pasture and meadow land.

Following the same model, phosphorus runoff can be estimated using equation 9. All slopes are assumed superior to 3% in this study. Under these assumptions, total runoff is given by the sum of a constant ($P_{runoff\_landuse}$) and a variable term that depends on the fertilization level ($P_2O_{5\ applied}$). Constant phosphorus runoff is assumed to be the ones of intensive permanent pasture and meadow land (0.77 kg $PO_4^{3-}.ha^{-1}.yr^{-1}$) Indeed, this land use is considered to be the closest to the farming system of this study. The phosphorus runoff emission factor from fertilizer application is 0.0044 kg PO_4^{3-} per kilogram of applied P or 0.0019 kg_{PO43-} per kilogram P_2O_5 applied.

$$\mathrm{P_{runoff}} = \begin{cases} 0 & slope < 3\% \\ \mathrm{P_{runoff\_landuse}} * \left(1 + \frac{0.2}{80} * \mathrm{P_2O_{5\ applied}}\right) & slope \geq 3\% \end{cases} \quad 9$$

<u>Nitrate leaching and runoff</u>

Nitrate leaching and runoff are modelled following the IPCC methodology for estimating indirect nitrous oxide emissions [226]. The IPCC methodology treats leaching and runoff together, without detailing how the two processes contribute to the total nitrogen loss. In this work, all losses of nitrogen from leaching and runoff are accounted as emissions to groundwater (leaching). The different sources of nitrogen addition to soil, are belowground residues, aboveground residues from harvest and senescence and urea application. For all sources, leaching factors of 24% and 22.5% are assumed for Europe under irrigated and rainfed conditions respectively. Emission factors are assumed constant across harvest scenario and crops. The emission factors assumed in this work are equivalent to 1.06 and 0.99 kg NO_3^- per kg of nitrogen addition for irrigated and rainfed condition respectively. As mentioned before, urea is assumed to have a nitrogen content of 46%. The nitrogen content of the different types of residue have already been detailed in previous sections (p29,p30 and p31).

Table **9** presents an overview of the nitrate emission for each source, accounting for its respective nitrogen content.

Table 9: Nitrate leaching from the different sources of nitrogen addition to soil.

Source	**Nitrate leaching from biomass residue (g NO_3^- / kg residue)**					
	Miscanthus		**Reed canarygrass**		**Switchgrass**	
	Irrigated	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**
$residue_{belowground}$	10.6	10.0	10.6	10.0	9.6	9.0
$residue_{harvest}$ (early)	5.1	4.8	10.4	9.8	9.2	8.7
$residue_{harvest}$ (late)	2.9	2.7	7.7	7.2	3.6	3.4
$residue_{senesced}$	4.1	3.9	8.8	8.3	5.2	4.9

	Nitrate leaching from urea application (kg NO_3^- / kg urea applied)	
	Irrigated	**Rainfed**
Urea	0.49	0.46

Emission factors are obtained as the product of the nitrogen content with the leaching factor of the irrigation scenario considered. Nitrogen content for residues can be found in Table 7, Table 4 and Table 8. Leaching factors are detailed in *Appendix 24*.

The IPCC methodology provides nitrogen leaching factor for both wet and dry climates. Under dry climates without irrigation, the leaching factor is assumed to be 0 while under wet climate or under dry climate with irrigation, 24% of the applied N is assumed to leach (Appendix 26). Based on the IPCC climate zone classification, most of Europe has a wet climate (Appendix 25) [236]. In the area of interest for this work, Spain and Greece are the two main countries with a dry climate. Thus, under irrigated conditions, the emission factor is assumed to be 24% of applied N for all Europe, in line with the methodology. However, under rainfed condition, 6% of Europe (Spain and Greece) is assumed to have a dry climate while the rest of Europe as a wet climate. An average European emission factor of 22.5% is computed from those assumption as the weighted average of the dry and wet climate emission factors.

Direct and indirect N2O

Direct emissions of nitrous oxide from nitrification and denitrification as well as indirect emission from volatilization, leaching and runoff of nitrogen were modelled based on the IPCC methodology [231]. The different sources of nitrogen addition to soil, are belowground residues, aboveground residues from harvest and senescence and urea application. Following the IPCC methodology, all sources contribute to direct and indirect emission from leaching.

However, only fertilizer application contributes to nitrous oxide emissions from volatilization. Emission from the different sources are modelled using European average factors. In line with assumptions made for ammonia and nitrogen dioxide emissions, the volatilized fraction of nitrogen applied as urea is assumed to be 15.3%. Nitrate leaching from all sources are modelled as described in the previous section (p35). As presented in Appendix 24, this work considers different emission factors for different source and irrigation scenarios. Table 10 presents an overview of the nitrous oxide emissions from each source, accounting for its nitrogen content.

Table 10: Direct and indirect nitrous oxide emissions from the different sources of nitrogen addition to soil.

Source	Direct nitrous oxide emissions from biomass residue (g N_2O / kg residue)					
	Miscanthus		**Reed canarygrass**		**Switchgrass**	
	Irrigated	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**
residue$_{belowground}$	0.092	0.089	0.092	0.089	0.083	0.080
residue$_{harvest}$ (early)	0.044	0.043	0.090	0.088	0.080	0.078
residue$_{harvest}$ (late)	0.025	0.024	0.067	0.065	0.031	0.030
residue$_{senesced}$	0.036	0.035	0.077	0.074	0.045	0.044
	Indirect nitrous oxide emissions from biomass residue (g N_2O / kg residue)					
residue$_{belowground}$	0.041	0.039	0.041	0.039	0.037	0.035
residue$_{harvest}$ (early)	0.020	0.019	0.041	0.038	0.036	0.034
residue$_{harvest}$ (late)	0.011	0.010	0.030	0.028	0.014	0.013
residue$_{senesced}$	0.016	0.015	0.034	0.032	0.020	0.019
	Direct nitrous oxide emissions from urea application (g N_2O / kg urea applied)					
	Irrigated			**Rainfed**		
Urea	11.0			10.9		
	Indirect nitrous oxide emissions from urea application (g N_2O / kg urea applied)					
Urea	3.4			3.3		

Emission from the different sources are computed following the IPCC methodology considering the emission factors presented in Appendix 24.

SOC stock changes

Soil organic carbon changes from land use change to perennial crops were modelled and quantified separately from the rest of the inventory. Two different methods were applied and compared as they capture different important features of SOC stock changes under perennial crops. The initial land use assumed in this work is cropland. Stock changes are modelled for a depth horizon of a 100 cm in both approach. Results are site-specific SOC stock change estimates for identified abandoned land with a spatial resolution of 5 arcminutes. The relationships between yield, irrigation level or harvest timing and SOC stock change are not considered in this analysis. The first method estimates SOC changes from the initial stock based on fixed empirical relative stock change values from (Qin, Dunn, 2016). Relative changes of 12.5%, 8% and 8% are assumed for miscanthus, reed canarygrass and switchgrass. Initial stock maps for a 100cm depth horizon were obtained from the European Soil Data Centre (ESDAC) [238]. The second approach uses a recently published empirical model for SOC stock changes prediction following land use change to perennial crops [239]. The model predicts relative stock changes following a transition from cropland to bioenergy grasses based on site-specific parameters (average temperature, clay content, bulk density) for a time horizon up to 20years. Site specific average temperature for Europe were obtained from the WorldClim database [240]. Bulk density and clay content maps were also obtained from the European Soil Data Centre [241].

When considered, land use changes often show the largest contribution to the overall GHG balance of the agricultural system considered [29, 104]. Due to the uncertainty surrounding the estimates from this work and to guarantee undistorted results, SOC changes were modelled separately from the rest of the inventory.

The agricultural reference system is a crucial parameter in assessing SOC changes from land use change [237, 239, 242, 243]. This work focuses on cropland that have been left abandoned for 5 to 28 years. Soil disturbance from agricultural practices are known to reduce SOC [244]. Land abandonment could therefore contribute to increase SOC content. However, damage to SOC stocks are long to reverse [245]. Thus, and despite the potential long time during which lands were left uncropped, the references system assumed is cropland.

The first approach used in this work is based on the results of a metadata analysis conducted by (Qin, Dunn, 2016). The authors reviewed data from worldwide field observation of major land use changes from cropland, grassland and forest to energy crop including switchgrass and miscanthus. The authors found average soil carbon changes of 12.5% and 8% following a transition from cropland to miscanthus and switchgrass respectively, for a depth horizon of a 100cm. Values were obtained across stand age and location. Based on these observations, SOC stock changes were modelled from initial SOC stock maps obtained from the European Soil Data Centre [238]. For reed canarygrass, SOC stock changes were assumed, based on the observation for switchgrass. Following recommendation from (Qin, Dunn, 2016), (Ledo, Smith, 2020), the depth horizon considered is 100cm. This approach allows for the modelling of differences between crops. Following this assumption, SOC stock increases 56% more under miscanthus than under switchgrass and reed canarygrass.

However, following this method, it is not possible to investigate the impact of stand age or climate on soil organic carbon changes. Yet, both parameters were found to be major influencing factors of SOC changes following LUC to perennial crops [237, 239, 242, 243, 246, 247].

Thus, an empirical model recently proposed by (Ledo, Smith, 2020) was used in a second time. The model is used to predict SOC changes following a transition from cropland to bioenergy grasses for a time horizon of 20 years. It uses soil bulk density, soil clay content and average temperature as explanatory variables of the change. Soil bulk density and clay content maps were taken from (Ballabio, Panagos, 2016) while average temperature were obtained from the WorldClim database [240]. The modelled was developped alongside a dataset on soil organic carbon changes under perennial crops. The dataset contains observations on miscanthus, switchgrass and reed canarygrass, but also observations on other perennial crops such as olive trees and short rotation coppice. The model was developped using all datapoints regardless of the crop and intend to model SOC changes under perennial crops in general . Following this approach, soil organic carbon changes are the same for all three crops. However, considering the large influence of climate on SOC changes, one could argue that a better accuracy is obtained by considering differences between climates than by considering differences between crops.
For both methods, results are 5 arcminute spatial resolution maps of SOC stock change from conversion of abandoned cropland to miscanthus, switchgrass and reed canarygrass. However, the geographical boundaries covered differ between approach. Indeed, while data on temperature and initial SOC stock were available for the entire area of the study, clay content and soil bulk density datasets did not cover countries outside of the European union boundaries.

Differences between irrigation treatment and harvest timing are not modelled in this study. The influence of biomass yield potential on soil carbon is also excluded from the analysis.

Process and input modelling

Input and agricultural processes were primarily modelled using existing Ecoinvent processes. A transport distance of 150 km was assumed for all inputs following (Moritz, Andreas, 2017), (Meyer, Wagner, 2017). Fuel consumption values for agricultural processes were modified in agreement with the data collected as part of this inventory (Appendix 20, Appendix **21** and

Appendix **22**). Emissions from diesel combustion were updated using the machinery-specific emission factor presented in (Nemecek and Kägi, 2007). Table 11 provides a summary of the main characteristics of the machinery assumed to be used in this study. A complete overview of the different Ecoinvent processes used in this analysis is provided in Appendix 27 and Appendix 28.

Table 11: fuel consumption and machinery characteristics for field operations

Operation	Unit	Weight[a] (kg)	Power[a] (kW)	Diesel consumption[b] ($l.unit^{-1}$)	Reference
Mowing – Rotary mower	(ha)	3943	50	5.1[c]	
Topping – Rotary mower - MSC	(ha)	3943	50	6.4	[249]
Topping – Rotary mower – RCG/SWG	(ha)	3943	50	5.1[c]	
Clipping – Rotary mower	(ha)	3943	50	5.1[c]	
Ploughing – Plough	(ha)	6339	78	23.20	[250-252]
Harrowing – Power harrower	(ha)	4883	62	13.8	[250-253]
Cultivating – Spring tine harrower	(ha)	4238	62	7.7	[251, 253]
Rolling - Roll	(ha)	4210	50	3.5	[251]
Lime application - Broadcaster	(ha)	3493	50	2.5	[110, 251]
Fertilizer application - Broadcaster	(ha)	3493	50	1.9	[250, 251]
Planting – Potato planter – MSC	(ha)	3747	50	16.8	[50, 53, 98, 135]
Planting – Seed drill – SWG/RCG	(ha)	3807	50	4.2	[110, 254]
Weeding – Field sprayer	(ha)	3777	50	2	[250, 251]
Cutting – Forage harvester – MSC	(tDM)	9445	150	1.4	[51, 135, 166, 167, 255]
Cutting – Rotary mower – SWG/RCG	(tDM)	3943	50	1.0	[110, 204]
Swathing – Rotary windrower	(ha)	3615	50	4	[251]
Balling – MSC	(bale)	5986	62	0.21	[166, 167, 255]
Balling – SWG/RCG	(bale)	5986	62	0.19	[88, 110, 136, 169, 201]
Bale loading	(bale)	3750	50	0.097[c]	

	Unit	Electricity consumption[d] (kWh)	Diesel consumption[d] ($l.unit^{-1}$)
Irrigation – Overhead sprinklers	(m^3)	0.36	0.00375

[a] *Weigth and power values from [220]*
[b] *Diesel consumption values from the reviewed literature as detailed in Appendix 20, Appendix* 21 *and Appendix* 22*, except otherwise specified.*
[c] *Standard Diesel consumption values from [220]*
[d] *Diesel and electricity consumption values are detailed in Appendix 23.*

2.3 Life cycle Impact assessment

This section presents the different assumptions and steps used to compute site-specific life cycle impacts and create impact maps using the compiled inventory, and the yield and water requirement maps. In total, five impact categories are considered for each one of the four scenarios investigated for all three crops.

2.3.1 Choice of impact categories and method

In this analysis, the midpoint life cycle impact assessment method ReCiPe, hierarchist, is used. The impact categories under consideration are: climate change(CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil resource scarcity (FRS). These categories were selected for their relevance for bioenergy production from perennial grasses as analysed by (Wagner and Lewandowski, 2017).

2.3.2 Impact assessment routine

As detailed in the previous section, the inventory compiled for this analysis is dependent on yield and irrigation volume estimates. For one hectare of land cropped with perennial grasses, part of the inventory will therefore vary following changes in yield and irrigation volumes estimates. Those include:

- Fertilizer requirement and associated emissions.
- Fuel and machinery requirement for harvesting operation, and associated emissions.
- Residue production and associated emissions.
- Fuel and machinery requirement for irrigation, and associated emissions.
- Water inputs for irrigation and associated emissions.

Therefore, the total impact from growing bioenergy crop on a certain area of land has three components. The first component aggregates all impact from farming operations that are not depending on the yield. Those include all the operations from the first year of cultivation, yearly swathing, and yearly use of a broadcaster for applying fertilizer. All inputs except from fertilizers are also included. The second component is yield-dependent. It gathers the impact from fertilizer use, biomass harvest, and residue production. Finally, the third component depends on the irrigation volumes. It bundles all impact from irrigation (energy use, water use, machinery…). This component is null under rainfed conditions.

Impact maps were computed in two steps using two different software. The LCA software SimaPro was used in a first time to compute preliminary impact results. While total impact maps were computed with MATLAB.

Yield and irrigation requirement are obtained under the form of maps with a spatial resolution of 5 arcminutes. For a map cell of latitude and longitude coordinate i and j, the total impact from biomass production for each category is computed following the routine described in Figure 4. The impact is computed from preliminary results obtained with SimaPro, the area of land suitable for farming in the cell ($Area_{i,j}$), the estimated yield for the cell (GAEZ $yield_{i,j}$), and the irrigation requirements for the cell (Irrigation $requirements_{i,j}$). Results are impact maps with a spatial resolution of 5 arcminutes.

Data were plotted using the software Panoply developed by the National Aeronautics and Space Administration (NASA). Data were either plotted as absolute impact per cell or plotted as impact per ton of dry matter produced.

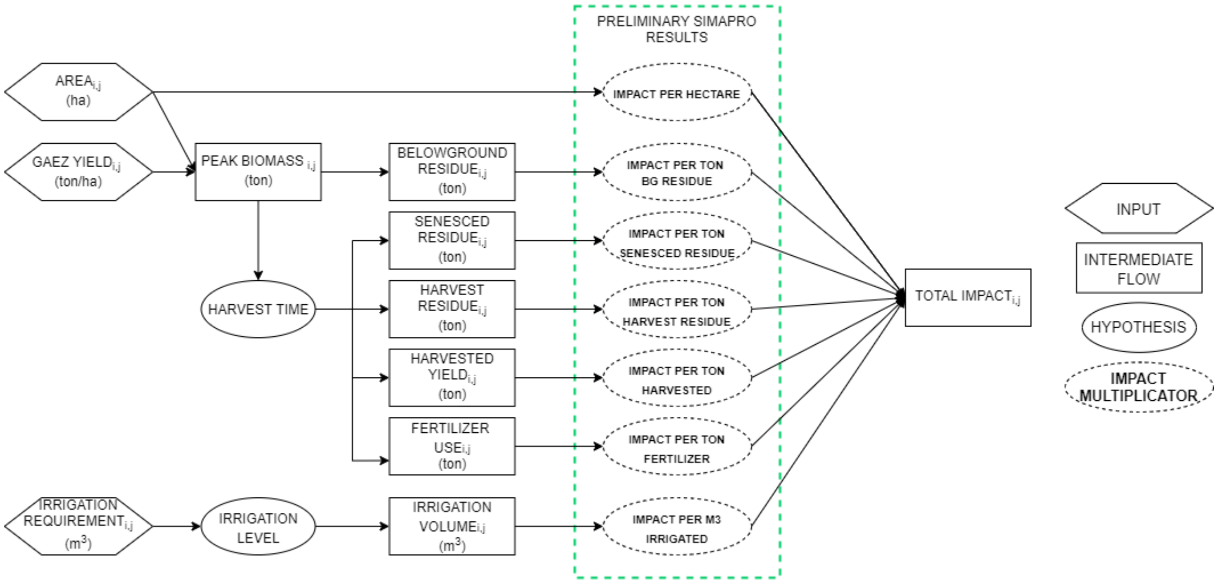

Figure 4: Impact estimation procedure

3 Results and discussion

3.1 Preliminary discussion

A preliminary step in understanding the results presented in this section, is the understanding of the yield patterns of the three crops under rainfed and irrigated conditions. Indeed, this work places yield at the centre of the life cycle inventory. Yields influence fertilizer requirement, fuel consumption, residue production and all related impacts. In addition, on a per tonne of dry matter basis, all impacts that are not related to yields such as the impacts from establishment will be discounted over the total dry matter production, giving lower impacts to biomass with higher productivity. As presented in the method, yield potential were not estimated in this work, but extracted from world maps presented in another study [65]. Yield potential maps for Europe, extracted from their work were already presented in Figure 2. Table 12 provides an overview of their results for both rainfed and irrigated scenario at a European scale with no constrain on land use.

Table 12: Bioenergy feedstock yield potential in Europe as found in (Næss, Cavalett, 2020)

Yield ($t.ha^{-1}$)	Miscanthus		Reed canarygrass		Switchgrass	
	Rainfed	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**
Mean	6.6	14.6	10.2	12.8	14.2	23.5
Median	6.0	13.5	10.5	12.9	14.3	22.9
Std	3.4	7.3	2.5	2.8	4.0	5.6
Maximum	22.6	37.0	17.1	20.4	29.6	38.1
Range	5.0-7.6	8.8-18.8	8.7-12.1	11.4-17.6	11.5-16.8	19.9-26.8

Yield levels reported here correspond to maximum agro-climatic yields under high input management in Europe as estimated with GAEZ. The entire European area is considered without constrained on land use. However, the area suitable for cultivation is crop-specific and estimated by GAEZ.
Mean yield values correspond to the average yield across the entire area suitable for the culture a specific crop.
The reported range correspond to the 5th quartile (lower value) and the 75th quartile (higher value).

According to their results, large differences both in terms of distribution and yield potential can be observed between the three crops. Reed canarygrass appears suitable for most of Europe while C4 grasses establishment and growth is drastically constrained past 57˚north. Under rainfed conditions, switchgrass shows the highest average yield potential, followed by reed canarygrass and Miscanthus. In Europe, this contradicts most observations that found miscanthus to be more productive than switchgrass, and in general C4 grasses to be more productive than C3 grasses under temperate climate [30]. Crop benefit from irrigation in two ways: yield increase under irrigated conditions, and new area become suitable for farming. On average, miscanthus, switchgrass and reed canarygrass yields increase by 121, 65 and 25% respectively. However, in absolute terms, switchgrass benefits more from irrigation than miscanthus and reed canarygrass due to higher initial yields. Thus, irrigation changes yield patterns and while switchgrass still shows the highest potential, average miscanthus yields become higher than average reed canarygrass yields. Finally, Switchgrass and reed canarygrass generally show relatively homogeneous yields. Miscanthus in the other hand displays very heterogeneous yields across Europe, which lowers average yield despite great maximum yield potential.

3.2 Environmental performance for Europe

3.2.1 Inputs and Outputs

Table 13 presents on overview of the different scenarios considered, at a European scale.

Table 13: Main characteristics of the different scenario

	Miscanthus				**Reed canarygrass**				**Switchgrass**			
	Rainfed		**Irrigated**		**Rainfed**		**Irrigated**		**Rainfed**		**Irrigated**	
	Early	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
Identified land[a] (10^6 ha)	8.8	8.8	15.3	15.3	14.3	14.3	15.2	15.2	11.7	11.7	15.4	15.4
Harvested biomass (10^6 tDM.yr^{-1})	59.6	41.7	205.4	143.8	155.2	114.8	214.9	159.0	173.6	118.0	368.8	250.8
Harvest residues (10^6 tDM.yr^{-1})	6.6	4.6	22.8	16.0	21.2	15.7	29.3	21.7	23.7	16.1	50.3	34.2
Senesced residues (10^6 tDM.yr^{-1})	-	19.9	-	68.5	-	45.8	-	63.5	-	63.1	-	134.1
Belowground residues (10^6 tDM.yr-1)	3.1	3.1	10.7	10.7	14.1	14.1	19.5	19.5	10.5	10.5	22.4	22.4
Number of bales (10^7 p.yr^{-1})	64.8	24.5	223.3	84.6	97.0	67.5	134.3	93.5	108.5	69.4	230.5	147.5
N fertilizer (10^4 tN.yr^{-1})	31.0	12.5	106.8	43.1	155.2	81.5	214.9	112.9	133.7	41.3	284.0	87.8
P fertilizer (10^3 tP.yr^{-1})	59.6	24.2	205.4	83.4	248.3	111.4	343.8	154.2	295.1	53.1	627.0	112.9
K fertilizer (10^4 tK.yr^{-1})	57.8	22.9	199.3	79.1	155.2	21.8	214.9	30.2	98.9	11.8	210.2	25.1
Water for irrigation (10^9 m^3.yr^{-1})	-	-	60.8	60.8	-	-	53.0	53.0	-	-	56.7	56.7
Average yield (tDM.ha^{-1}.yr^{-1})	6.8	4.7	13.4	9.4	10.9	8.0	14.1	10.5	14.8	10.1	23.9	16.3

[a] *The area of abandoned cropland is obtained from [65]*

The total areas of abandoned agricultural land suitable for growing miscanthus, reed canarygrass and switchgrass are 8.8, 14.3 and 11.7 million hectares respectively, under rainfed conditions, and 15.3, 15.2 and 15.4 million hectares respectively, under irrigated conditions. The pattern for culture on abandoned agricultural land only, is therefore slightly different from the previously described pattern with no constrain on land use. Indeed, reed canarygrass benefits less from its potential in northern latitude due to the limited area of abandoned agricultural land identified in Scandinavia (Figure 1). In the other hand, under rainfed conditions, both switchgrass and reed canarygrass benefit greatly from their potential in eastern Europe where large areas of abandoned land were identified (Figure 1). Under irrigated conditions, the areas suitable for growing each crop are comparable. This is because the vast majority of abandoned land is located within the geographical boundaries suitable for farming all three crops with water supply (Appendix 1, Figure 1).

The maximum total annual biomass production potentials in Europe (early harvest) from miscanthus, reed canarygrass and switchgrass are 59.6, 155.2 and 173.6 $MtDM.yr^{-1}$ respectively, under rainfed conditions and 205.4, 214.9 and 368.8 $MtDM.yr^{-1}$ respectively, under irrigated conditions. Irrigation therefore increases biomass yields by 131% on average across crops. Following our assumptions, early harvested yields are equal to the yield potential from GAEZ, as found in (Næss, Cavalett, 2020). From a biomass production perspective, switchgrass and miscanthus shows the most and the least interesting potential, respectively, for both irrigated and rainfed conditions. While this could be expected for switchgrass considering its higher average yield, it is surprising that miscanthus has a lower potential than reed canarygrass despite higher average European yields (Table 12). It can however be explained by the distribution of abandoned agricultural lands. As previously mentioned large amount of abandoned land are located in Eastern Europe (Figure 1). While the culture of miscanthus is feasible on those lands under irrigated conditions, its yields remain low when compared to the ones of reed canarygrass (Appendix 1).

The ranking of the total biomass production potential is the same for a delayed harvest scenario. Indeed, similar relative overwinter losses were assumed for all three crops (30, 26 and 32%). In the other hand, the absolute amount of senesced residue shows considerable variations across scenarios due to large differences in the level of peak standing biomass. The amount of senesced residue rises with increasing biomass production and therefore with irrigation. The same trend is observed for belowground residue from renewal as belowground biomass is assumed to linearly increase with aboveground peak biomass. Finally, harvest residues are assumed proportional to the standing biomass and will therefore be lower for a delayed harvest or for biomass with a lower productivity, like miscanthus.

The number of bale produced in Europe from the harvested biomass varies along with the fresh matter yield. In most cases, a moisture content of 15 or 20% was assumed following field drying and the number of bales produced per ton of dry matter will be similar. However, for miscanthus biomass harvested in autumn (early harvest), the number of bale produced per ton of dry matter is far superior than for the other scenario. This is a result of the assumption that miscanthus biomass harvested in autumn had a moisture content of 54%. Under rainfed conditions, the absolute amount of bale produced are therefore comparable for miscanthus harvested in autumn and reed canarygrass harvested in spring, despite large differences in dry matter yield (59.6 and 114.8 $MtDM.yr^{-1}$ respectively).

Fertilizer requirement for Europe vary with the European total biomass production and the biomass nutrient content. Irrigation therefore increases fertilizer requirement by 131% on average following the increase in yields. Delaying harvest in the other hand, reduces nutrient requirements as it reduces biomass production and biomass nutrient content. Average nitrogen requirement across water supply for instance, are reduced by 60, 48 and 69% for miscanthus reed canarygrass and switchgrass respectively. The stronger decrease for switchgrass is a consequence of higher overwinter loss and larger decrease in biomass nitrogen content.

Finally, total yearly water requirement for irrigated conditions are 60.8, 53.0, 56.7 cubic kilometers for miscanthus switchgrass and reed canarygrass. Those volumes are obtained from GAEZ as the ones required for an optimal biomass growth without water stress. As the area that can be cultivated is similar for all crops under irrigated conditions, water requirement and yield can easily be related. Miscanthus show the highest relative increase in yield of all three crops and reed canarygrass the lowest. Accordingly, water requirement is highest for miscanthus and lowest for reed canarygrass. The high response of miscanthus yields to irrigation are in line with observations [24]. However, it was also reported that miscanthus could produce more biomass per unit of water than Switchgrass [24]. In this work, the absolute yield increase per additional unit of water is however higher for switchgrass (3.44 kg $DM.m^3$) than for miscanthus (2.39 kg $DM.m^3$).

3.2.2 Total European impact breakdown

For each of the scenario detailed in Table 13, the breakdown of the total European environmental impact into key elements of the cropping system is presented in Figure 5. The breakdown is presented here in a first place as its understanding is necessary to understand variations in the total impact.

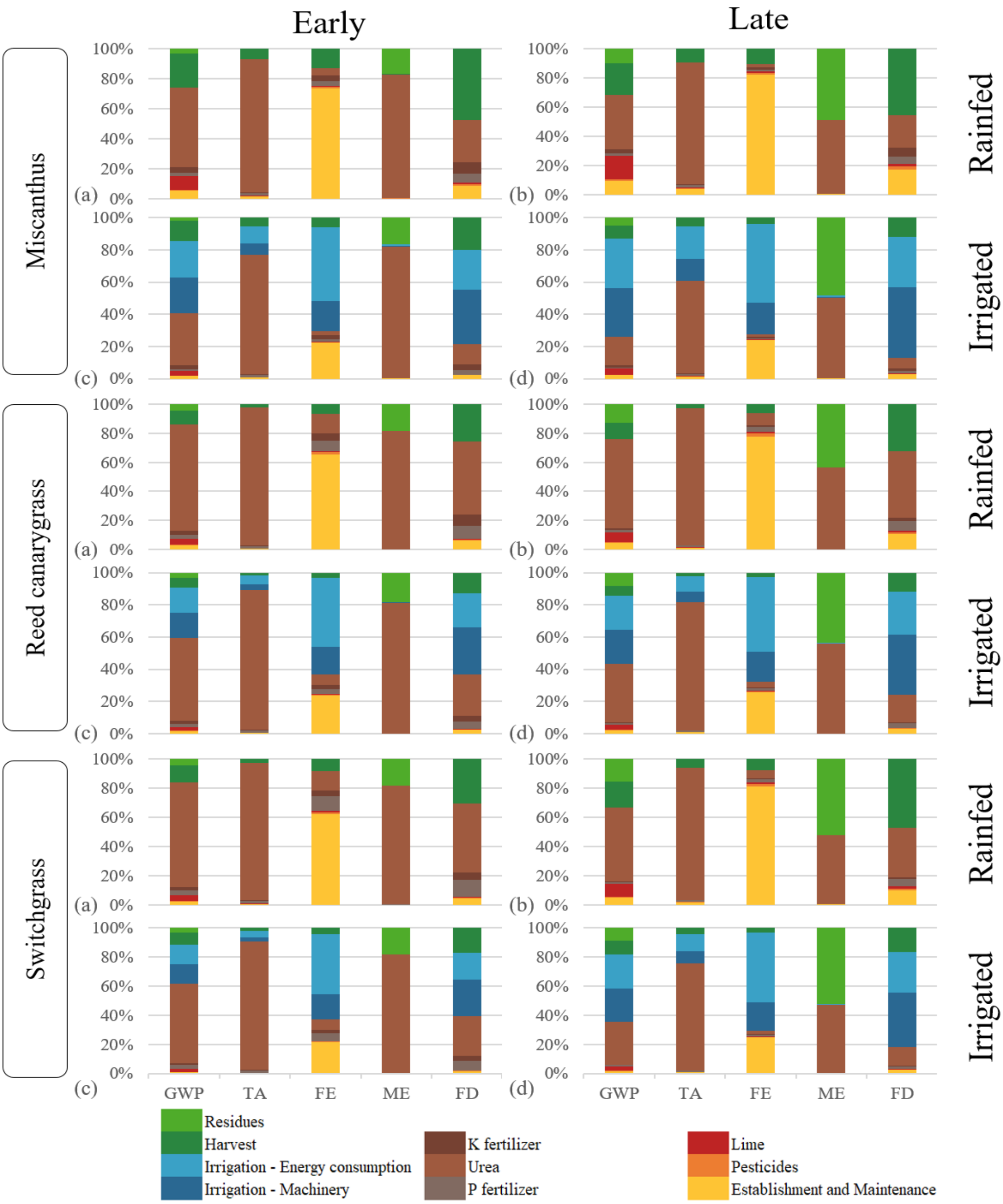

Figure 5: Relative contribution of key elements of the cropping system to the total European LCA impact of miscanthus, reed canarygras and switchgrass for 4 different scenarios. (a) early harvest, rainfed. (b) late harvest rainfed. (c) early harvest, irrigated. (d) late harvest, irrigated.

Fertilizers, and especially nitrogen fertilizers appear to be a key contributors to all impact categories for all plants and all scenarios. Under rainfed conditions, urea production and use accounts for 57 and 92% of total CC and TA impacts, therefore being the largest contributor to these impact categories. Under irrigated conditions, its contribution to these impact categories is reduced down to 37 and 77%, on average across plant. Urea is also the largest contributor to the ME impact in the case of an early harvest. Its contribution is however reduced in a delayed harvest scenario as the contribution from senesced residues increases. Finally, to a smaller extent, the use of nitrogen fertilizer is also a large contributor to fossil ressource scarcity. These ranges compare well with values reported in other studies who identified nitrogen fertilizer to be the greatest contributor to the impact categories CC, FRS and ME [59, 104]. On average, the contribution of nitrogen fertilizer to the overall impact is higher for switchgrass and reed canarygrass than for miscanthus. This can be explained by the lower nitrogen content of the miscanthus biomass and the associated reduced nitrogen requirement.

Under irrigated conditions, the irrigation process is the largest contributor to FE and FRS impacts. On average across harvest management ans crop, it accounts for 64 and 60% of the total FR and FRS impacts. It is also a major contributor to the CC impact, contributing 42% on average and to the TA impact. The high contribution of the irrigation process to the FE impact can be explained by the assumption made on the electricity mix. This study considers the European electricity mix and the FE impact can ultimately be related to coal mining. Another important feature of the irrigation process is that the impact from energy consumption and the impact from machinery production have the same order of magnitude. When compared to other studies, the contribution of the irrigation process to the different impact categories appears high [104]. However, for the CC and FRS impact categories, our estimates compare well with the results from (Schmidt, Fernando, 2015). Differences observed with (Escobar, Ramírez-Sanz, 2017) can most likely be attributed to differences in system boundaries and electricity mix. Indeed the authors only accounted for energy consumption and used the spanish electricity mix.

Harvesting operations are important contributors to the FRS impact and, in some cases, the CC impact. This contribution can be explained by the machinery and fuel intensive process of harvesting and balling. This observation is especially true for early harvested miscanthus as a consequence of its high moisture content.

The large contribution from establishment and maintenance to the FE impact is a consequence of the modelling approach. Indeed, as presented page 34, phosphorus losses are estimated with the SALCA-P model which assumes total phosphorus emissions to be the sum of a constant, and a variable term. While the variable term is related to P fertilizer use, the constant term which is the largest of the two, is accounted for in the maintenance operations.

A transition from an early harvest system to a delayed harvest system decreases the contribution of all fertilizer to all environmental impacts. This is expected from the reduction in fertilizer use. In contrast, the contribution of residues increases as a consequence of biomass senescence.

Overall, the majority of impact arise from elements of the system that are linearly increasing with yield (fertilizer requirements, intensity of the harvesting operation, residue accumulation). While this is a modelling assumption it also shows that impact arising from operation that are not depending on yield have a low contribution to the overall impact. In such conditions, there is little room for optimization as the total impact and the yield are mostly proportional.

3.2.3 Total European impact

Table 14: Total European impact for different scenarios

	Miscanthus				Reed canarygrass				Switchgrass			
	Rainfed		**Irrigated**		**Rainfed**		**Irrigated**		**Rainfed**		**Irrigated**	
	Early	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
CC (10^9kg $CO_{2\,eq}.yr^{-1}$)	8.2	4.7	47.1	34.8	29.7	18.6	59.3	43.7	26.0	11.5	74.1	42.8
TA (10^6kg $SO_{2\,eq}.yr^{-1}$)	128.5	54.8	529.3	275.4	598.4	318.1	908.3	520.1	519.3	166.5	1187.0	437.2
FE (10^6kg $P_{eq}.yr^{-1}$)	3.9	3.5	22.8	21.3	7.2	6.0	21.2	19.6	6.1	4.7	23.4	20.4
ME (10^6kg $N_{eq}.yr^{-1}$)	25.1	16.6	93.1	61.9	127.5	97.3	189.1	144.5	109.8	58.4	249.6	133.3
FRS (10^9kg $oil_{eq}.yr^{-1}$)	1.5	0.8	11.3	8.8	4.2	2.4	11.4	8.9	3.8	1.7	14.0	9.4

Total impact from biomass production in Europe for different scenarios. The five impact categories considered are: CC: Climate change; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; FRS: Fossil resource scarcity

In the light of the observations presented in the previous section (p 46), nitrogen fertilizer use, irrigation, residue accumulation and harvesting operations appear to be the major drivers of all impact categories with the exception of freshwater eutrophication under rainfed conditions. In this context, differences in total impacts can be accurately explained by changes in yield, irrigation, nutrient requirement per unit of yield and residue accumulation.

Higher yields will generate larger impacts by increasing fertilizer use, residue accumulation and increasing the intensity of harvesting operations. The yield pattern therefore translates into an impact pattern where switchgrass and miscanthus respectively display the highest and lowest total European impact for similar agricultural system.

Similarly, impacts will be larger under irrigated conditions following the increase in yield and the additional impact from irrigation itself. On average, yields increase by 132% under irrigated conditions (Table 13). Accordingly, fertilizer-related impacts, residue-related impacts and harvesting operation-related impacts will also increase by 132% on average In total, the CC impact, for instance, increases by 300% on average across plant and harvest time for an irrigated scenario. Generally speaking, for all three crops, impacts under irrigated conditions are always higher than impact under rainfed conditions, irrespective of the harvest time, with the exception of terrestrial acidification. Indeed, reed canarygrass and switchgras show a lower TA impact for a delayed harvest of biomass under irrigated condition than for an early harvest of biomass under rainfed conditions. This differences can be explained by changes in the fertilizer requirements per unit of biomass. This difference is not observed for miscanthus due to the large increase in total biomass production under irrigated conditions.

Absolute total impacts are reduced in the case of a delayed harvest. This reduction is primarily the consequence of the reduction in nutrient requirements and especially nitrogen nutrient requirements. The drop in yield levels also reduces impacts from the harvesting operations. In contrast, the impact from residue accumulation increases but the overall result is a net reduction of the total ME impact.

3.2.4 Average impact per tDM

The average impact per ton of dry matter are presented in Table 15. These values correspond to the average across Europe and were obtained as the ratio of total impacts by total biomass production.

Table 15: Average European life cycle impact from the production of one ton of dry biomass from Miscanthus, Reed canarygrass and switchgrass under different management.

	Miscanthus				**Reed canarygrass**				**Switchgrass**			
	Rainfed		**Irrigated**		**Rainfed**		**Irrigated**		**Rainfed**		**Irrigated**	
	Early	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
CC (kg $CO_{2\,eq}$.tDM^{-1})	138	106	229	229	192	162	276	275	150	96	201	168
TA (dag $SO_{2\,eq}$.tDM^{-1})	216	124	258	181	386	277	423	327	299	139	322	172
FE (g P_{eq}.tDM^{-1})	66	80	111	140	46	53	99	123	35	39	63	80
ME (g N_{eq}.tDM^{-1})	421	377	453	407	822	847	880	909	632	488	677	524
FRS (kg oil_{eq}.tDM^{-1})	25	17	55	58	27	21	53	56	22	14	38	37

Average impact per ton of dry matter computed as the ratio of the total European impact by the total European biomass production. The five impact categories considered are: CC: Climate change; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; FRS: Fossil resource scarcity

Considering all crops, the climate change impact per ton of dry matter harvested ranges from 106 kg CO2 eq. tDM^{-1} under rainfed conditions to 276 kg CO2 eq.tDM^{-1} under irrigated conditions. This values compare well with others reported in the literature [43, 59, 180]. (Sanscartier, Deen, 2014) reported CC impact to range from 90 to 170 kg CO2 eq.tDM^{-1} for miscanthus grown under rainfed conditions. (Kiesel, Wagner, 2016) investigated the environmental performance of miscanthus and switchgrass grown under rainfed conditions and reported lower values ranging from 50 to 137 kg CO2 eq. tDM^{-1}. In the other hand, CC impacts under irrigated conditions are lower than impacts reported by (Escobar, Ramírez-Sanz, 2017). The authors reported 700 kg CO2 eq. tDM^{-1} for switchgrass produced under irrigated conditions in spain.

Regarding other impact categories, results from this work compare well with estimated impact of miscanthus biomass production as modelled in Ecoinvent [257].

In the literature, Studies comparing the environmental performance of switchgrass and miscanthus generally find lower environmental impact for miscanthus [59, 60]. This can primarily be related to a common assumption that miscanthus produces larger amounts of biomass for much lower fertilizer requirements [59, 60]. In our work, input are modelled to match a specific yield, and while differences in nutrient requirements per ton produced are considered, they are small when compared to assumptions made elswhere [59, 60]. In addition, miscanthus yields assumed in this work are generally lower than switchgrass yields which increases the impact per ton from constant operations. The combination of this two factors explains why miscanthus and switchgrass show comparable impact per ton harvested.

For the same harvest time, impacts per ton of dry matter increase in all categories with water supply due to the additionnal impacts from the irrigation process. For instance, under irrigated conditions, the CC impact per ton of dry matter increased by 90, 56 and 55%, on average, for miscanthus reed canarygrass and switchgrass respectively. The observed increase is larger for miscanthus than for the other crops due to the higher water consumption per ton of dry biomass produced. For other impact categories, while value differ, this trend remain observable and impact increase more under irrigation for miscanthus than for the other crops.

For the same irrigation level, impacts per ton of dry matter produced generally decrease for a delayed harvest. This trend can be explained by the reduced nutrient content and therefore, nutrient requirement, of the overwintered biomass. Under irrigated conditions however, the trend is more contrasted. Indeed, as yield decrease over winter, water consumption per ton of harvested biomass increases. To some extent, the reduction of impact from decreased fertilizer use per ton of dry matter are offset by the increased impact from irrigation. While net gain can be observed for switchgrass due to its high water efficiency, lower benefits can be observed for the two other crops. An exception to the decreasing pattern is the FE impact which can be explained by the modelling assumptions. Indeed, the impact arising from the constant term used to model phosphorus losses, is shared by a lower total biomass under a delayed harvest assumptions. The modelled FE impact per tonne of dry matter is therefore higher for late harvest than for early harvest.

3.3 Environmental performance – Spatial variability

3.3.1 Influence of different agricultural system on the spatial variability

Figure 6 presents an overview of the spatial variability of the different impacts at a cell level. (ie: the median means that 50% of the cell have an impact value superior than the median and 50% have an impact value lower than the median). The interest of looking at the impact at a cell level is that it corresponds to the real total impact that would arise from biomass production in a certain area. Previous observations about the influence of different agricultural system on the environmental performance of biomass production are clearly visible. Irrigation for instance, increases impacts across Europe while delaying harvest reduces impacts at the cell level.

In addition, Figure 6 provides input on the spatial variability of different impacts. Impact will vary spatially in response to changes in the processes from which they arise. In the case of freshwater eutrophication for instance, under rainfed condition, the impact mostly arise from the culture of the field and the associated P leaching. From one cell to the other, variations in the FE impact will therefore mostly arise from differences in the area of abandonned land within the cell. In the other hand, other impacts such as CC, TA, ME and FRS will mostly vary in response to changes in fertilizer requirements, irrigation requirements, residue production (harvest timing) and thus ultimately yields, and irrigation volumes.

For these reasons, not only does irrigation increases impacts per cell, but irrigation also amplifies the spatial variability of the different impact categories. Two main reasons can explain this trend. First, the area of abandonned agricultural land contained in each cell is greatly variable across the map (Figure 1). Second, irrigation requirements are site specific and vary with climate. As the combination of these two factors, irrigation impacts are very cell-specific and geographically variable. Considering the importance of irrigation for a number of impact categories, it is expected that irrigation would have a large influence on both the average impact and its geographical spread. In contrast, the impact per cell displays less variability in Europe under rainfed conditions.

Similarly, delaying harvest reduces the spatial variability of impacts per cell for all categories. This is a consequence of the modelling approach that assumes overwinter losses to be proportional to the maximum standing biomass. By doing so, yields losses are higher in cells with higher production and lower in cell with lower production. As yield converge, so does the

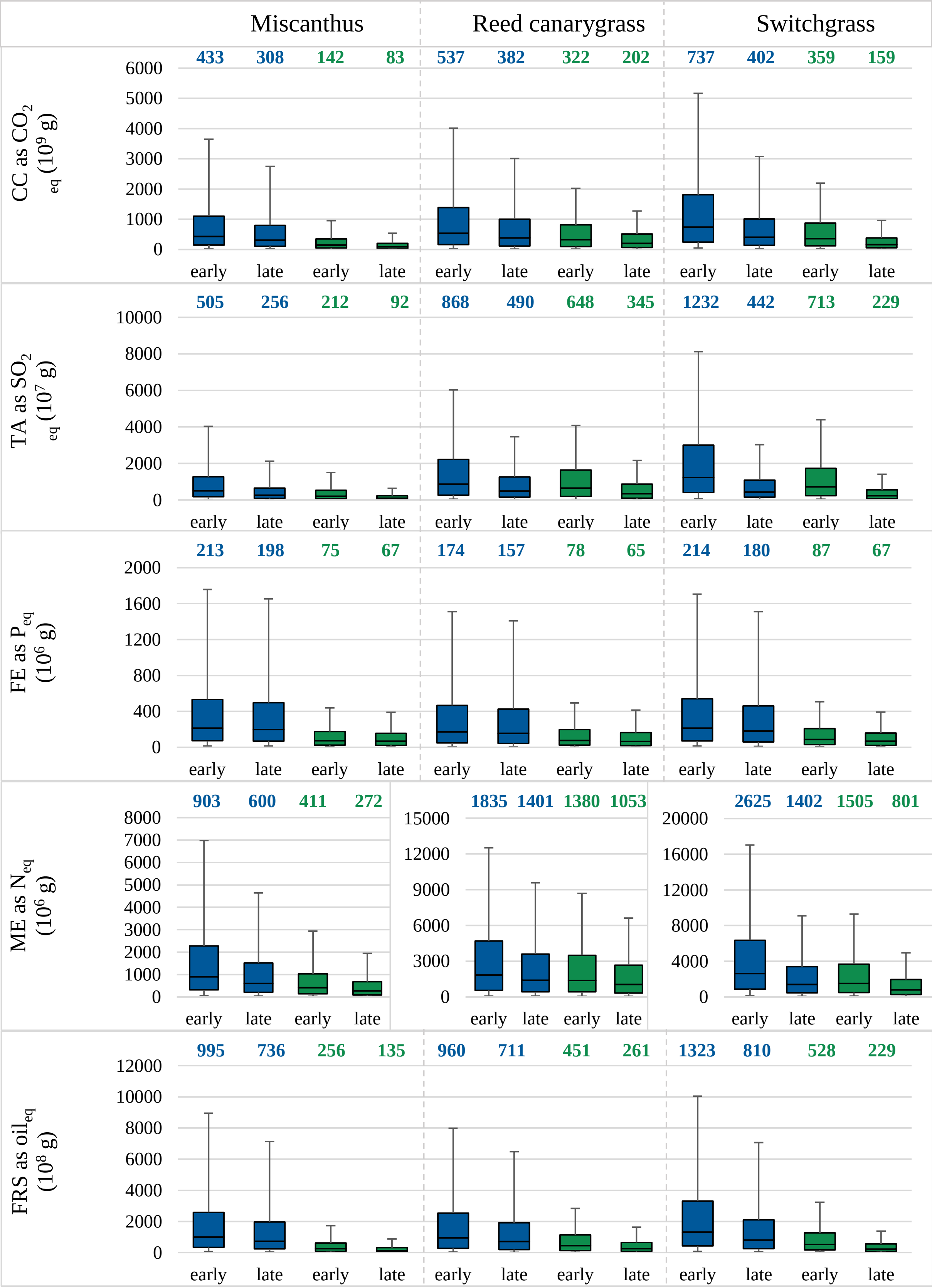

Figure 6: Life cycle impact per cell from the production of biomass from Miscanthus, Reed canarygrass and Switchgrass in Europe during one year under different management scenarios. Impact per tonne of dry matter were computed for each cell by dividing the total yearly impact for the cell by its yearly biomass production. Cell resolution is 5 arcminutes. Latitude considered: (34-72)˚N. Longitude considered (-25-48) ˚E. Green plots and values correspond to rainfed scenarios while blue plots and values correspond to irrigated scenarios. Early refers to early harvest while late refers to delayed harvest. Impacts: CC, climate change; TA, terrestrial acidification; FE, freshwater eutrophication; ME, marine eutrophication; FRS, fossil resource scarcity. Nonparametric boxplot: The bottom and top of the box are the first and third quartiles. The line inside the box is the second quartile (median). The tip of the whiskers represents the 5th and 95th percentiles. Given values are the medians for each scenarios.

impact from fertilizer use and harvesting operations and therefore the impact per cell. In other word, for a delayed harvest system, stands will be more similar to one another across Europe. In such circumstances, while yield still plays a dominant role, a large share of the variability can also be attributed to changes in the area containned in each cell.

Figure 7 in the other hand presents the spatial variability of impacts on the basis of 1 ton of dry matter produced. Impacts per tonne of dry matter were obtained for each cell, by dividing the total impact for each category by the total biomass production withing the cell. Observations made earlier (p 50) are also visible. On average across cell, irrigation increases impacts per tonnes of dry matter across all crops and categories, if considering similar harvest timing. (ie: under irrigated conditions, impact per ton increase in most of the cells of the map).

As for the European average impact (p 50), results are more contrasted when looking at the influence of a delayed harvest. On average across cell, a delayed harvest decreases the CC, TA and FRS impacts per tDM for all crops but miscanthus. For switchgrass and reed canarygrass the net gain can be attributed to reduced nutrient requirement. In the case of miscanthus, as already explained, this difference can be attributed to the high water requirement per unit of biomass harvested. However, as the first quartile shows, a delayed harvest can decrease impact per ton of dry matter under irrigated conditions in certain cell for miscanthus too. The FE impact increases for a delayed harvest due to modelling assumptions as detailed p 50.

These results highlight that the spatial variability is reduced if considering impacts per ton of biomass harvested rather than impact per cell. First, variability is reduced as the impacts per ton of dry matter does not depend anymore on the area cropped within the cell boundaries. Second the variability is reduced as impact arising from fertilizer use, residue accumulation and harvesting operations are constant on a per tDM basis. These will only change from a scenario to another but not spatially. Spatial variations can therefore be attributed to the irrigation process and elements of the agricultural system that are not yield dependent (lime, establishment operations…) These results also demonstrated that while one agricultural system can improve the environmental performance of biomass production in some areas, it might be detrimental in others.

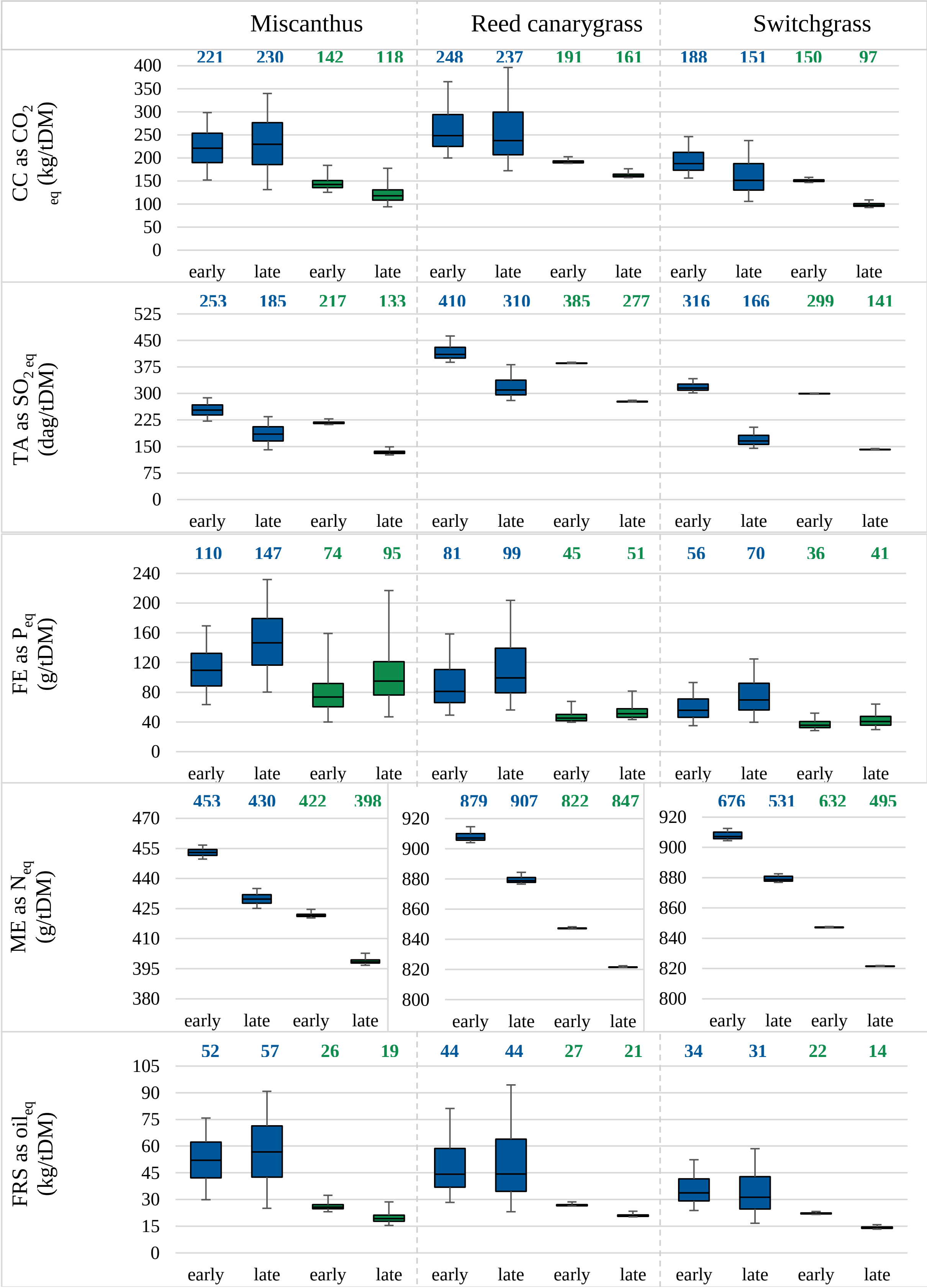

Figure 7: Life cycle impact from the production of 1 t dry biomass from Miscanthus, Reed canarygrass and Switchgrass in Europe under different management scenarios. Impact per tonne of dry matter were computed for each cell by dividing the total yearly impact for the cell by its yearly biomass production. Cell resolution is 5 arcminutes. Latitude considered: (34-72)˚N. Longitude considered (-25-48) ˚E. Green plots and values correspond to rainfed scenarios while blue plots and values correspond to irrigated scenarios. Early refers to early harvest while late refers to delayed harvest. Impacts: CC, climate change; TA, terrestrial acidification; FE, freshwater eutrophication; ME, marine eutrophication; FRS, fossil resource scarcity. Nonparametric boxplot: The bottom and top of the box are the first and third quartiles. The line inside the box is the second quartile (median). The tip of the whiskers represents the 5th and 95th percentiles. Given values are the medians for each scenarios.

3.3.2 Impact maps

Maps of impact are displayed as impact per tDM and total impact per cell.

The first kind (Figure 8) presents the impact per ton of dry matter produced. In such maps, all impact related to yield variations are constant. As explained, variability is drastically reduced as the elements of the agricultural system that depend on yield are also the ones that contributes most to all impact categories (fertilizer, harvest, residues) However, such map can be used to identify areas where growing perennials is most efficient. Under rainfed conditions, these will be the areas with the highest yield. Indeed, constant burden from establishment and maintenance will be shared by a largest biomass production. Under irrigated conditions and considering the influence of irrigation on the total impacts, these will correspond to areas where the yield gain per unit of water input are the highest.

The second kind (Figure 9) presents where total impact would originate if biomass was to be cropped. It allows to identify areas where pressure will be more important due to highest yield or larger area of abandonned land. However, comparing the environmental performance of biomass production in different location is not possible.

Maps of climate change impact are presented in Figure 8 and Figure 9. As mentioned, under rainfed condition, the CC impact per ton of dry matter decreases with yield. This is because constant impact associated with the use of the land is shared by a larger biomass production. As shown in Figure 8, for miscanthus, areas showing the lowest CC impact are around the alps and in the Mediterranean region. For reed canarygrass and switchgrass, the lowest impact is observed in central regions of Europe. In contrast, the worst CC impact is observed in northern Europe for miscanthus only, and in far eastern Europe for all three crops. Reed canarygrass is the only crop able to grow in northern Europe but the associated CC impact is rather high. Under irrigated conditions, for all three crops, the lowest impacts are observed around the alps and the Carpathian mountains while the highest impact is observed in dry regions of the Mediterranean basin and in far eastern Europe.

For other impact categories, a similar pattern is observed (Appendix 29, Appendix 30, Appendix 31 and Appendix 32)

Regarding impacts per cell, impact are the greatest where the biomass production is the greatest. The amount of biomass produced per cell appears to be primarily dependent on the area of land that is cropped within the cell boundaries. For this reason, the total climate change impact

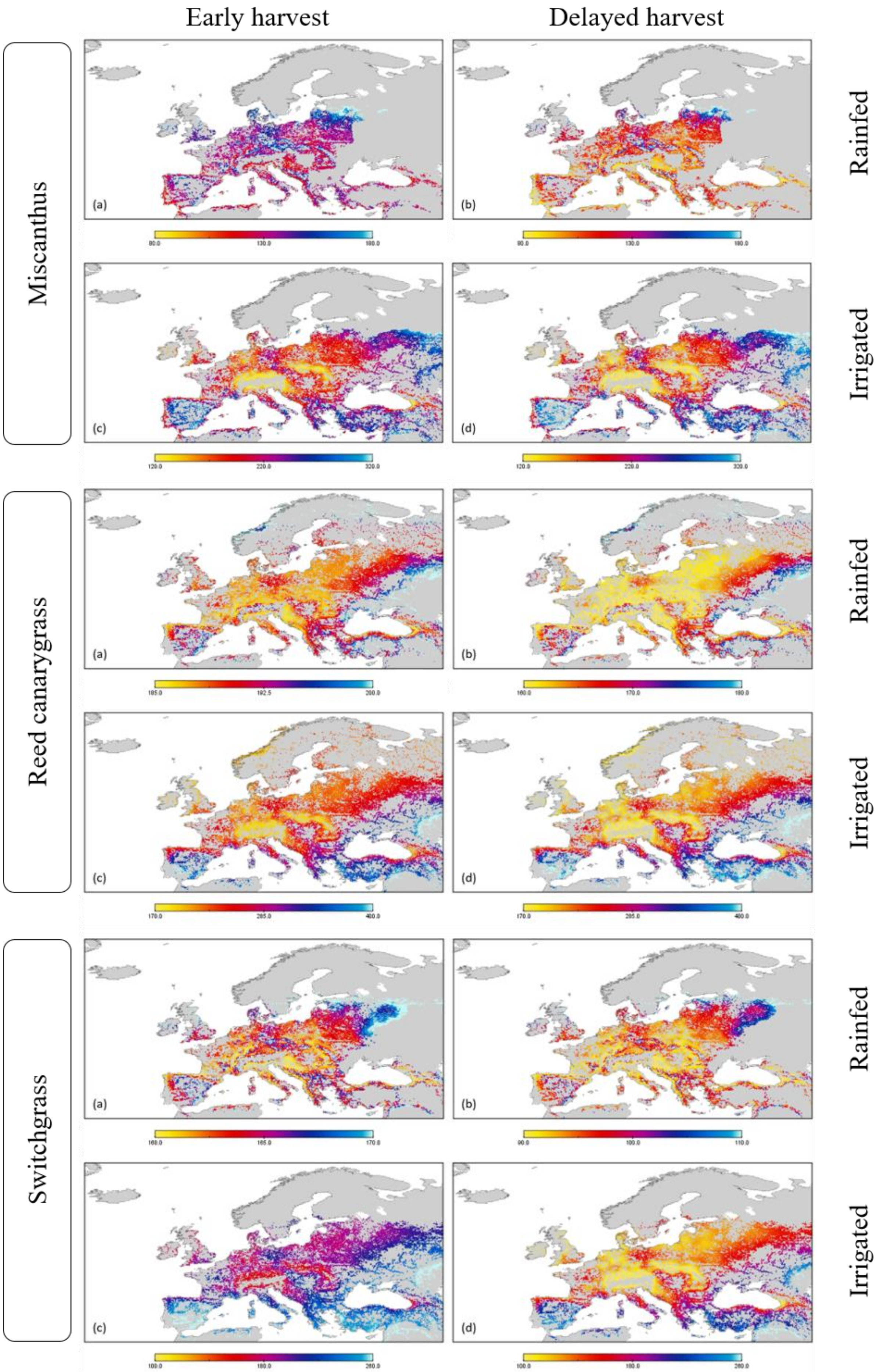

Figure 8: Life cycle climate change impact from the production of 1 tonne of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/tDM) produced. Map scales are based on 5^{th} and 95^{th} percentile and are map-specific.

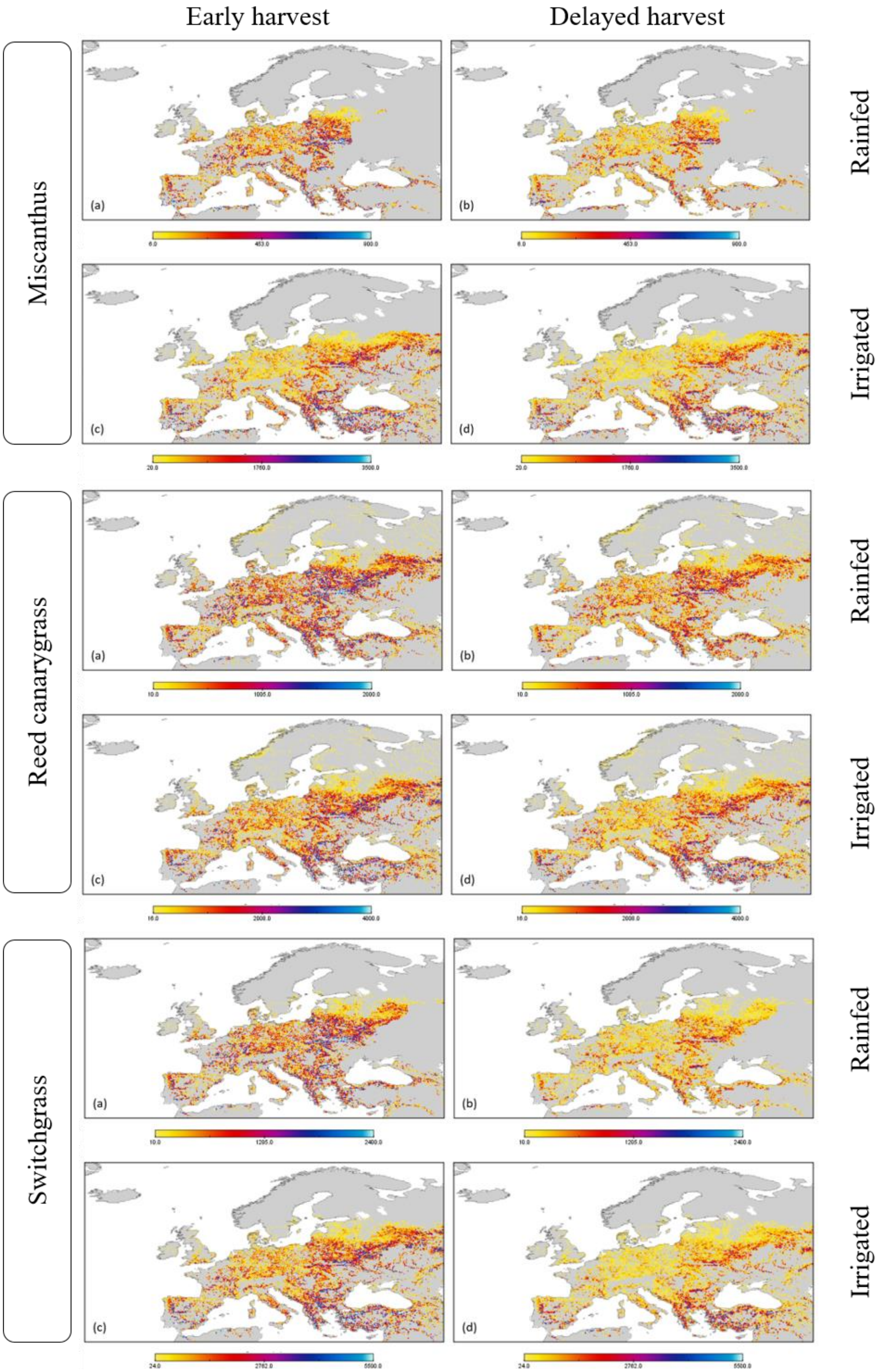

Figure 9: Total life cycle climate change impact from the production of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe during one year. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/yr) produced. Map scales are based on 5th and 95th percentile and are map-specific.

follows the pattern of identified abandonned lands (Figure 1). Highest impacts are observed where the area available is the largest. In these conditions, the highest impacts are observed in eastern Europe. Other maps for the total impacts are in Appendix 33, Appendix 34, Appendix 35 and Appendix 36

3.4 Benefits and tradeoff from different agricultural system

3.4.1 Benefits from delaying harvest – CC

Under rainfed conditions, delaying harvest until late winter or early spring consistently reduces impact per ton of dry matter across Europe. This is a consequence of the lowest nutrient uptake per ton harvested. Delaying harvest is interesting mostly in areas with relatively high yields. In area with low yields, a larger share of the impact is driven by constant elements (lime, establishment) Delaying harvest does not influences these absolute impact and rather increases their contribution to the impact per ton of dry matter.

Under irrigated conditions, delaying harvest can both increase or decrease CC impact per ton of dry matter. For switchgrass under irrigated conditions, delaying harvest consistently reduces the Cc impact per ton of dry matter. In contrast, for miscanthus and reed canarygrass, while impact decrease in central Europe by delaying harvest, they increase in Far eastern Europe and around the Mediterranean basin. A reason for the differences observed is that water requirements per additionnal ton of biomass produced are higher fr miscanthus and reed canarygrass than for switchgrass. When delaying harvest, less biomass is harvested for the same water supply. Acordingly, the impact from irrigation per ton of dry biomass harvested increases. In the other hand, as nutrient content in the harvested biomass drops, the impact from fertilizer use decreases. In areas where low yield increase are achieved for high water consumption, delaying harvest result in a net increase of the CC impact per ton. On the contrary, in areas where biomass production increases with rather low amounts of irrigated water, the CC impact is reduced by delaying harvest.

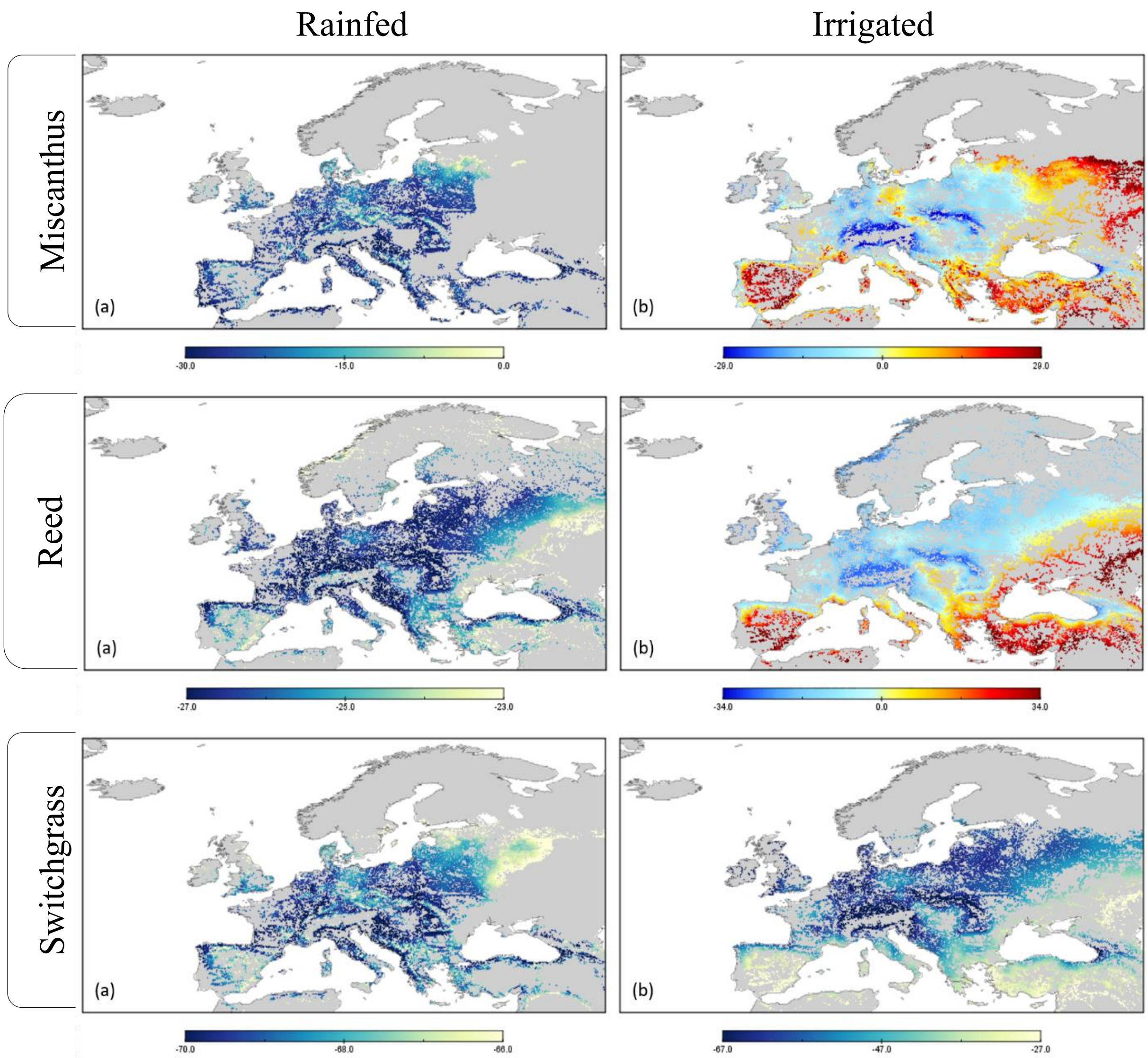

Figure 10: Changes in climate change impact per ton of dry matter from delaying harvest. The two scenarios considered for each crop are: (a) rainfed; (b) irrigated. Impacts displayed in % change considering early harvest as the reference. Map scales are based on 5th and 95th percentile and are map-specific.

3.5 Soil organic carbon changes

As presented in p37, two different methods are applied to quantify soil organic carbon changes. The main reason is that to our knowledge, no method currently exists for modelling soil organic carbon changes considering both, crop and site-specific parameters. The first method intends to illustrate the variability in soil organic carbon sequestration potential between the crops while the second intend to show the influence of site-specific drivers on this potential.

3.5.1 First approach

Absolute changes in soil organic carbon stock, considering a depth of 100cm are presented in Figure 11.

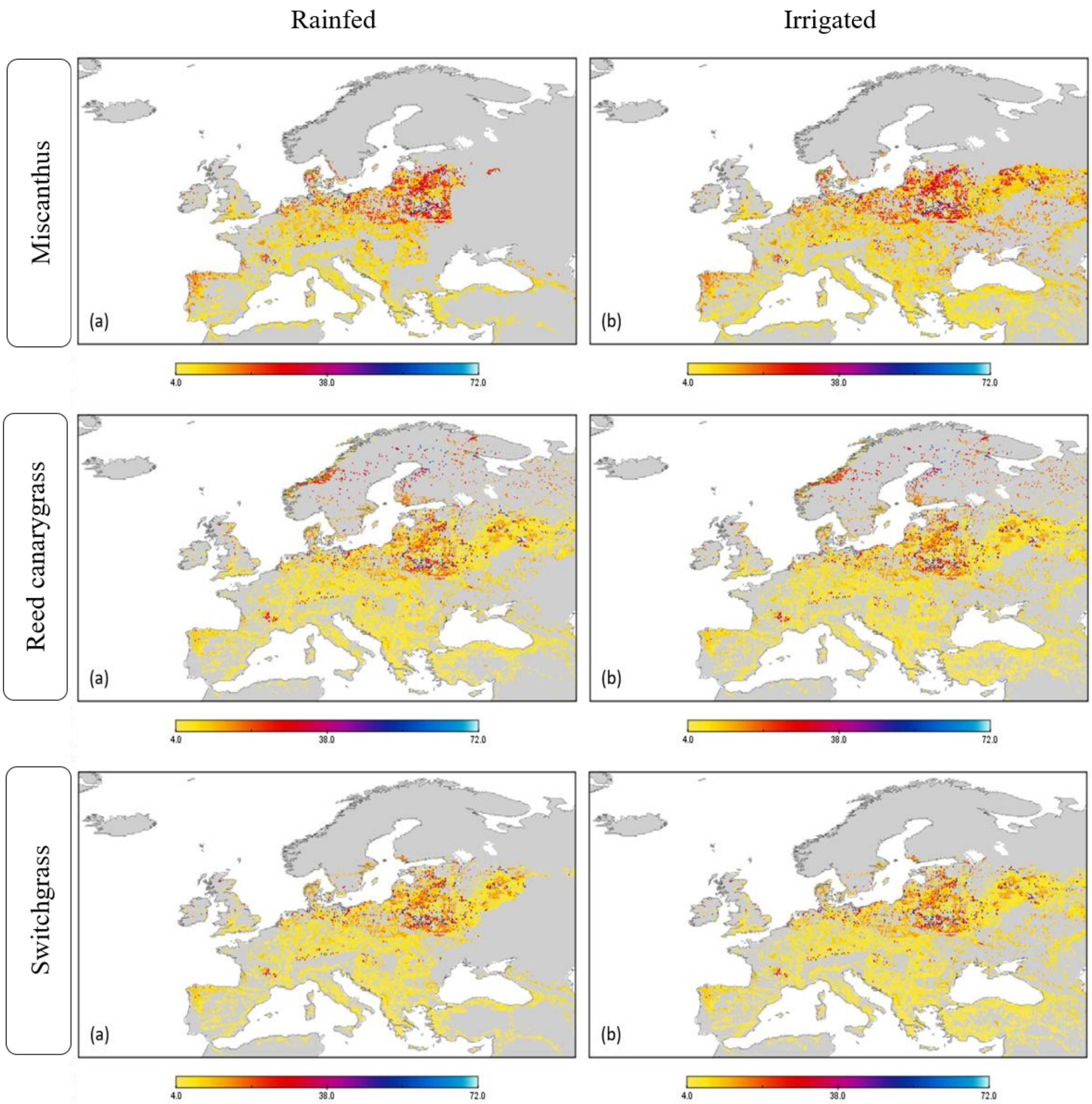

Figure 11: Soil organic carbon stock changes under perennial crops to a depth of 100cm. The two scenarios considered for each crop are: (a) rainfed; (b) irrigated. Changes are displayed in $tC.ha^{-1}$.

Generally speaking, the increase in soil organic carbon stock appears larger in the north, north-east of Europe than in central of Southern Europe. This observation is valid for all three crops and reflect the higher initial carbon content of the soil in northern latitudes (Appendix 37).

Regarding the different plants, the median increase in stock across Europe are 9.6, 6.7 and 6.3 $tC.ha^{-1}$ for miscanthus, reed canarygrass and switchgrass under both rainfed and irrigated conditions. Average SOC stock increase for miscanthus, reed canarygrass and switchgrass are 15.4, 10.9, 10.3 $tC.ha^{-1}$ under rainfed conditions and 14.5, 10.6, 9.8 $tC.ha^{-1}$ under rainfed conditions. Changes in the average stock increase between rainfed and irrigated conditions can be explained by the larger proportion of land with high initial stock under rainfed conditions. In other words, in the new area that irrigation opens for farming, a lower number extreme initial stock values are observed. Differences between switchgrass and reed canarygrass are observed despite similar assumptions. The differences are due to the larger area suitable for reed canarygrass than for switchgrass in northern latitude where the predicted stock increase is the largest.

Estimates reported here are higher than found in the literature [49, 239]. (Ledo, Smith, 2020) reported an average increase of $5.7tC.ha^{-1}$ for transition from cropland to perennial crops. However, assuming a lifetime of 17, 15 and 8 years for miscanthus, switchgrass and reed canarygrass such increase in stock would translate in average European sequestration rates of 0.9, 1.1, and 0.68 $tC.ha^{-1}.yr^{-1}$ under rainfed conditions and 0.85, 1.1 and 0.65 $tC.ha^{-1}.yr^{-1}$ under irrigated conditions. This is assuming that the stock change computed here correspond to the maximum stock change at the end of the stand lifetime, and before soil is disturbed by stand renewal. These sequestration rates are within the range of reported values in the literature for switchgrass and miscanthus [52, 237, 247, 258]. A reason that could explain that stock change estimates are on average too high is that yearly sequestration rates decrease with time as the soil reaches a new equilibrium [237, 239]. Therefore yearly sequestration rates are unlikely to be maintained at high level over a long period of time and therefore it is unlikely that stock change increase of the level that is estimated here will be achieved.

In the investigated area, maximum changes for miscanthus, reed canarygrass and switchgrass are 147, 96 and 96 $tC.ha^{-1}$ under both irrigated and rainfed conditions. According to the method applied here, these values are associated with the highest initial C stock. These extreme values nevertheless compare well with extreme values found in a recently compiled harmonized dataset on soil organic carbon changes under perennials [239]. In this dataset, increase in SOC stock of a 100 $tC.ha^{-1}$ are reported for both miscanthus and switchgrass.

Finally, while irrigation generally decreases the average SOC stock increase accross Europe, in absolute term, irrigation would result in large net SOC stock increase following the expansion of the cropped area.

3.5.2 Second approach

SOC stock change estimates using the second approach are presented in Figure 12. This approach uses an empirical model that estimates relative changes of the SOC stock under perennial crops from site specific parameters (temperature, bulk density and clay content). The geographical range of results displayed here is limited by the availability of data on clay content and bulk density outside of the European Union (Appendix 38 and Appendix 39). Following this model, changes in soil organic carbon are negatively correlated to the average temperature, crop age and clay content but positively correlated to the soil bulk density. The model identified temperature as the most influencing parameter. This model doesn't allow the differentiation between the three crops and for this reason results are displayed for three different stand age rather then three different crops. SOC stock changes are also displayed for the entire area of abandonned cropland with no constrain on land suitability for either of the crop.

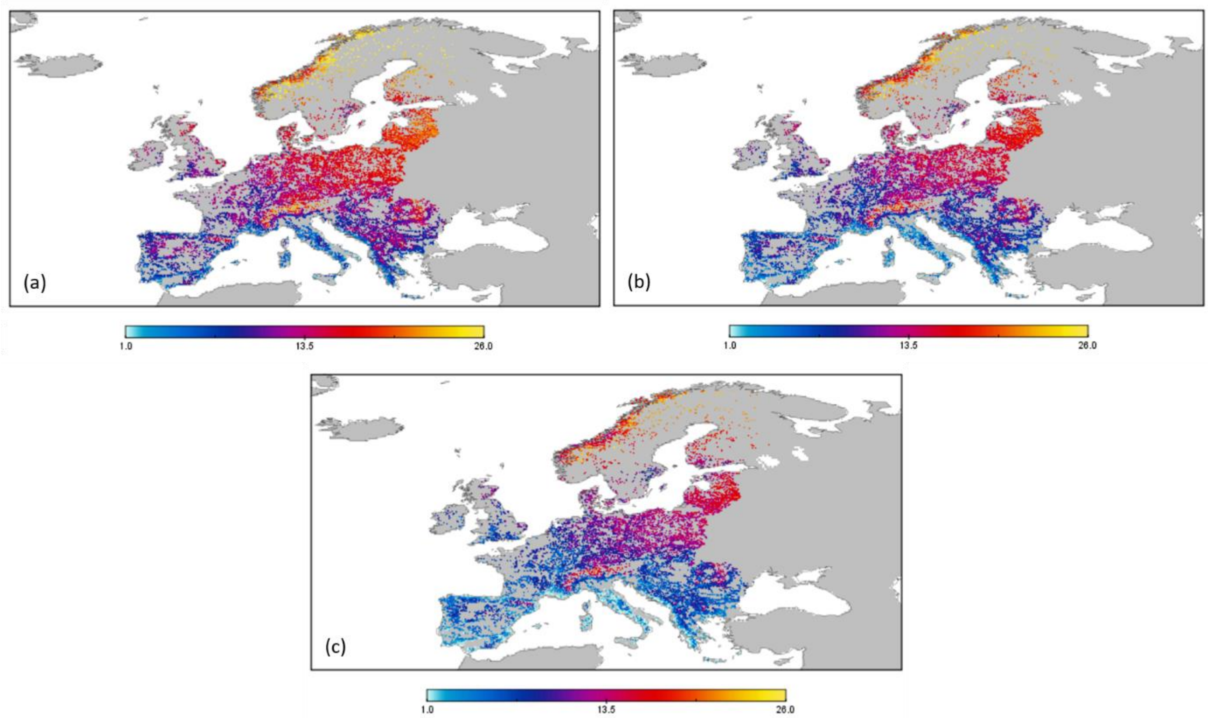

Figure 12: Relative soil organic carbon changes under perennial crops for different stand age. (a) 10 years; (b) 15years; (c) 20 years. Relative changes in %. Map scales are based on the lowest 5th percentile of all three maps and the highest 95th percentile of all three maps

Surprisingly, a similar pattern to the one obtained with the first method is observed. The largest changes are observed in the north-north east of Europe while the lowest changes are observed in the south and around the Mediterranean sea. As explained, differences are mainly driven by differences in average temperature. This explains very well why larger changes are observed in colder regions of northern Europe and in the colder montaneous regions of central Europe than in the warmest climates of the south. The similarities between these results and and the ones obtained with the first approach suggest that initial soil organic carbon reflect to a certain extent the local climatic conditions.

Another important parameter accounted for in this approach is the time dependency of the trend in soil organic carbon change. According to the model the relative soil organic carbon change decreases with time. To a certain extent, this is in line with the observation that a new equilibrium is reached within 20 years [239]. The establishment of a stand is indeed, associated with large amounts of soil organic carbon inputs in the first years. Under the form of roots, rhizomes or above ground residues, large quantities of carbon accumulates after the transition to perennial crops. As time passes, new inputs are offsets by soil organic carbon degradation and finally, a new equilibrium is reached. While several papers agree that soil organic carbon changes under perennial crops converge toward zero within 20 years [237, 239], the model seems to predict that degradation can overshoot new carbon inputs. These results are in contradiction with several studies that showed a continuous increase of the soil organic carbon stock with time, until saturation [237].

Both of the approach considered here have different strength and limitations. They however both identify the north, northeast of Europe as a potential hotspot for SOC sequestration. In this area of Europe, not only is the sequestration potential per hectare the highest, but the area of abbandonned cropland on which could be grown perennial crops is also relatively large (Figure 1). In these norther latitudes, switchgrass or reed canarygrass could be grown on larger areas than miscanthus and therefore yield greater carbon sequestration benefits despite lower sequestration rates per hectares. Similarly, by increasing the area that can be cropped, irrigation could increase the sequestration potential.

3.6 Limitations

3.6.1 Yield estimates

The results presented in this work, both in terms of biomass production potential and in term of environmental impacts depend primarily on the yield estimates obtained from GAEZ. While the geographical distribution of suitable land for each crop is sensible considering their specific ecological requirements, yields estimates appear to contradict certain observations.

As previously discussed p 43, GAEZ finds switchgrass to be the highest yielding of the three crop considered under both rainfed (avg 14.2tDM.ha^{-1}) and irrigated (avg 23.5tDM.ha^{-1}) conditions. In contrast, miscanthus average yields are relatively low under rainfed conditions (avg 6.6tDM.ha^{-1}) and miscanthus only ranks second under irrigated conditions (avg 14.6tDM.ha^{-1}). Reed canarygrass in the other hand shows medium yields with low spatial variability under both rainfed (avg 10.2tDM.ha^{-1}) and irrigated (avg 12.8tDM.ha^{-1}) conditions.

These results are in contradiction with many field observations accross Europe who consistently report yields ranging 10-20 tDM.ha^{-1} for established stands of miscanthus under rainfed conditions [47, 48, 98, 101, 148, 161, 259, 260]. Other models such as MISCANFOR, a crop-productivity model specifically developed and calibrated for miscanthus predict yields superior to 20tDm in most regions of Europe [261]. (Kalinina, Thumm, 2016) concluded that miscanthus was currently the highest yielding C4 grass in temperate climates and one of the strongest perennial energy crop.

Side by side trials comparing switchgrass cultivars and miscanthus yields generally shows a greater potential for miscanthus under temperate climates [32, 59, 159, 263]. In an extensive literature review, (Heaton, 2004) found that miscanthus average yields were more than double the ones of switchgrass across similar climates. This trend is expected under most European conditions due to the longer stay green period of miscanthus and despite lower radiation use efficiency [264]. Thus, European scale study have assumed lower yields for switchgrass than for miscanthus [60].

In addition, while miscanthus yields may seem low in absolute terms but also when compared to the one of switchgrass, average switchgrass yield appear high when compared to the yield commonly achieved. (Tubeileh, Rennie, 2016) reported that commercial yields commonly achieved for switchgrass ranged 10-13tDM.ha^{-1} which is lower than the average European yield estimate from GAEZ

Finally, reed canarygrass generally shows lower yield than C4 grasses in temperate climate. (Powlson, Riche, 2005) reported that yields of 8tDM.ha^{-1} are routinely achieved for reed canarygrass in the UK while switchgrass and miscanthus generally reach 10 and 12 tDM.ha^{-1} respectively. Reed canarygrass is however the most competitive in northern Europe due to its higher cold resistance [30]. This explains why reed canarygrass is mostly cropped in Finland and Sweden [23].

The reasons for the discrepancy between yields estimates from GAEZ and field observations are not investigated in this work as this was out of the scope of this study. However considering the influence of yield on fertilizer use, residue accumulation and harvest intensity, important differences would be observed for different yield estimates. The discrepancies in yield potential assumed from GAEZ constitute a major limitation of this work and make the comparison with other work difficult.

3.6.2 Nutrient requirements

As other work before, this thesis demonstrate the importance of fertilizer consumption in determining the environmental performance of biomass production [59, 104]. In this work, it is assumed that the sustainable production of biomass requires to supply all removed nutrient with artificial fertilizers. The environmental cost of this assumption is large and touches all impact categories. While soil mining should be avoided to maintain soil quality, other sources of nutrient and especially of nitrogen were disregarded. Nitrogen deposition rates are high in parts of Europe [265] and it was reported that under certain condition, nitrogen fertilizer use could be avoided [30, 147].

In our work, the elements of the farming system that have the greatest impacts increase linearly with the yield. Therefore, while areas with higher farming efficiency were identified, the fraction of the total impact that can be optimized is reduced. Future work could investigate the relationship between nutrient requirements and site specific parameters such as nitrogen deposition. Much greater benefits could indeed be achieved if less nutrient were required per harvested ton.

3.6.3 Influence of the harvest timing on the agricultural system

Two harvest times are considered in this work, the first one maximizes biomass and the second one minimizes nutrient requirements per ton harvested. The two system considered are very theoretical and disregards important factors that would determine the feasibility of one or the other. The economic dimension for instance is not considered. In addition harvest time is assumed to influence only three parameters in this work. These are, the winter losses, the nutrient content of the biomass, and the moisture content of the biomass. While these are the main parameters that change, other changes are ignored. Stand longevity can be reduced in the case of an early harvest as it prevent full relocation of nutrient to the belowground biomass [49, 137, 147]. This may not only impair long term yields but also early seedling vigour and increase weed competition. A reduction of the stand lifetime would be detrimental to the environmental impact of biomass harvested early in the season.

Besides, while winter losses are considered, they are assumed constant across Europe. European studies have reported a strong influence of the local environment on the extent of overwinter losses [148]. It was also shown that while absolute losses between early and late harvest varied spatially, daily losses showed less variability [49, 148]. Assuming a constant ratio across Europe is an important limitation of this work and a better spatial resolution could have been achieved by considering site specific yield reduction, based on daily losses.

3.6.4 Irrigation modelling

As presented p 46 the irrigation process as a large influence on the environmental performance of the crops for different impact categories. While irrigation volumes are site specific, the irrigation process itself is assumed to be the same for all location. It is created from four standard Ecoinvent processes that were designed for France, Germany, Spain and Switzerland. One of the limitation of this approach is that processes for western Europe might not reflect the technologies that would be used in eastern Europe. Another limitation is that these processes as defined in the Ecoinvent database share many common assumptions. The French, German and Spanish processes are identical and the only difference between these three and the irrigation process designed for Switzerland is the electricity consumption per unit of water irrigated.

Studies that have investigated the impact from irrigation have found great spatial variation per unit of volume irrigated [266]. Differences mainly arise from the water source (groundwater or surface water) and the technology used [266]. Both are known to vary greatly across Europe [267]. For this reason, future research could improve the accuracy and spatial resolution of this analysis by accounting for the spatial variability of the irrigation process itself. In addition, it would be possible to investigate how irrigation volume and water sources affect the different local water reservoirs.

3.6.5 Soil organic carbon

Two different methods are applied to investigate changes in soil organic carbon following land use change to perennial crops (details p 37). The first one intend to capture the differences in SOC sequestration potential that exist between the three crops. The second method is used to investigate the influence of spatially variable parameters such as climate and soil characteristics. Previous studies have highlighted the importance of all these parameters when assessing potential SOC change [237, 239]. However, to our knowledge, among the method currently existing for modelling SOC changes under perennial crops, none accounts for both the differences between crops and the influence of parameters that vary spatially.

The results obtained using the first method suggest larger increase in SOC in soil with large initial stock. However, studies have shown that higher initial soil organic carbon could reduce the sequestration potential as larger losses could arise from conversion. The conversion of grassland to perennial crops for instance generally shows a negative soil carbon balance [237, 239].

Results obtained using the second method suggest that relative SOC stock change decrease with stand age. In other words, changes would be superior after 10 years than after 20 years of cropping. While the literature generally agrees that yearly SOC change rates decrease with time and converge towards zero within 15 to 20 years, observations generally show a continuous increase in soil organic carbon during this period [237, 239, 243]. Thus, the results of the empirical model published by (Ledo, Smith, 2020) are in contradiction with other empirical observations [237, 239, 247] and represent a major limitation of this modelling approach.

Another major shortcoming of the two methods employed is that sequestration potential are assumed independent from crop yields. Assuming similar changes for crops with different productivity is believed to be unrealistic. Indeed, soil organic carbon accumulates from biomass production. While sources vary (aboveground residue, belowground residue…), it ultimately comes from photosynthetic activity and thus yield.

The influence of different harvest time and irrigation scenario are disregarded despite their importance. Indeed, yield loss from overwintering biomass is, to some extent c gain for the soil [49, 268]. The sequestration potential is therefore expected to increase for a delayed harvest. Following certain land use change, precipitation were also found to influence soil organic carbon gain or loss [269]. By increasing soil moisture content irrigation could also influence sequestration potential. However this was also excluded from the analysis.

Soil organic carbon changes, when included in the life cycle analysis, generally show the greatest contribution to the climate change impact [29, 104]. In that respect, the analysis presented here is incomplete and future work should focus on accounting for soil organic carbon changes following the transition from cropland to perennial grasses. In the case of abandoned agricultural land, attention should be drawn on the alternative land use. Indeed, in the past decade, forest have been expending on abandonned agricultural land in Europe [60]. If perennial grasses were to be cropped on abandonned cropland this process will most likely stop. The potential increase in soil carbon from a transition to forest is commonly referred to as foregone carbon and could yield greater mitigation benefits than the production of perennial grasses for bioenergy [60]. An accurate estimate of the mitigation potential from bioenergy grown on abandonned cropland should therefore include this dimension.

4 Conclusion

By the end of the century a substantial increase in bioenergy production is expected as part of the global effort to maintain average global warming below 2 degrees above pre-industrial levels. Their potential large scale development is however compromised by the evident trade-off that would arise from increased land competition. Abbandonned agricultural lands have recently been identified as the most promising area for bioenergy production with minor impacts.

This work explored the biomass potential and environmental performance of bioenergy feedstock production from three perennial grasses (miscanthus, reed canarygrass and switchgrass) on abandonned agricultural land in Europe. The area and spatial distribution of abandonned agricultural lands were obtained from a previous work conducted by (Næss, Cavalett, 2020). Maximum yield potential for Europe, under rainfed and irrigated conditions are based on the GAEZ model and obtained from the same authors. In addition, two harvest timing were considered for each water supply level. That is, an early harvest that maximizes biomass production and a delayed harvest that minimizes fertilizer requirement per unit of harvested biomass. In total 12 yield scenarios are considered for Europe. A spatially explicit life cycle inventory that varies with yield and irrigation requirement was compiled for each crop, from the reviewed literature. Five impact categories are considered for their relevance to bioenergy production: CC, TA, FE, ME and FRS. For each category, site-specific impacts were thereafter computed at a spatial resolution of five arcminutes for latitudes ranging between 34 and 72 degrees north and longitude ranging between 24 degrees west and 48 degrees east. Soil organic carbon changes were modelled separately for the same geographical range, using two different approaches. The first approach assumes SOC stock increase of 12.5, 8.5 and 8.5% of the initial stock for a transition to miscanthus, reed canarygrass and switchgrass respectively. The second approach uses a recently published empirical model to estimate soil carbon stock changes from site specific parameters (average temperature, soil clay content, soil bulk density) [239].

For Europe, the maximum total biomass production is estimated to be 60, 155, 174 Mt DM for miscanthus, reed canarygrass and switchgrass under rainfed conditions, and 205, 215, and 369 Mt DM under irrigated conditions. Irrigation therefore increases average biomass production and associated fertilizer requirements by 131%. In the other hand, delaying harvest over winter decreases biomass production by 29% on average and N, P and K requirements by 59, 65 and

78% respectively. Absolute water requirement for irrigated condition are highest for miscanthus and lowest for reed canarygrass however water requirement per aditionnal tDM produced are highest for reed canarygrass (888m^3/tDM) and lowest for switchgrass (291m^3/tDM). Therefore, not only is the yield increase under irrigated conditions highest for switchgrass, but the biomass gain per unit of irrigation is too.

Urea appears to be a key contributor the the impact categories CC, TA, ME, FRS, contributing 47, 83, 66 and 30% of the total impact on average across crops and management scenarios. Under irrigated conditions, the irrigation process itself appears to contribute 42, 17, 64 and 60% of the total CC, TA, FE, and FRS impact respectively, on average across crop and harvest timing. Our results also suggest that the machinery use for irrigation can make a significant contribution to the total impact and that it should not be excluded from the system boundaries. Finally our results show that if nutrients are applied to match site-specific requirements, most impact linearly increase with yields living little space for optimization.

Total European climate change impact ranges from 5 to 74 Mt $CO_{2\ eq}.yr^{-1}$ across scenario. Accross scenarios, TA ranges [55-1187] kt $SO_{2\ eq}.yr^{-1}$, FE ranges [4-23] kt $P_{eq}.yr^{-1}$, ME ranges [17-250] kt $N_{eq}.yr^{-1}$ and FRS ranges [0.8-14]Mt $oil_{eq}.yr^{-1}$. Delaying harvest reduces the total European CC, TA, FE, ME and FRS impacts by 62, 46, 87, 65 and 63% respectively, on average across scenario. Irrigation in the other hand increases European total impacts by 300, 187, 339, 149 and 469% for CC, TA, FE, ME and FRS respectively.

Climate change impact per ton of dry matter range from 106 kg CO2 eq. tDM^{-1} to 276 kg CO2 eq.tDM^{-1}. Generally speaking switchgrass displays better environmental performance per ton harvested than miscanthus who displays better performance than reed canarygrass. Irrigation strongly increases the impact per ton of all three grasses. In the other hand, delaying harvest generally decreases impact per ton of dry matter with the exception of miscanthus and reed canarygrass under irrigated conditions.

Our results show that the production of biomass from perennial grasses would be most effective in regions surrounding mountains in central Europe and in Eastern Europe for reed canarygrass and switchgrass. However, if large scale production was initiated, large impacts would arise in Eastern Europe due to the large area of abbandonned lands and the high yield potential of most crops in this area.

SOC change estimates consistently identify the north of eastern Europe as a hotspot for carbon sequestration. This also corresponds with an area with large amounts of abandonned cropland.

The first approach also suggest that despite lower soil organic carbon changes under reed canary grass and switchgrass, their total sequestration potential might be higher than the one of miscanthus due to their larger geographical adaptability.

Our results show that the production potential and the environmental performance of switchgrass are generally better than for the two other crops. This is in contradiction with previous LCA studies that found miscanthus to have lower impacts [59, 60]. Our results show that delaying harvest could greatly improve the biomass environmental impact while irrigation worsens the performance. This supports the delayed harvest system generally applied in Europe [150]. It also supports the conclusion that irrigation for bioenergy production should generally be avoided as the additional environmental burden is too high [1]. Our results also show the large potential for biomass production and soil organic carbon sequestration in eastern Europe.

The accuracy of the results presented in this report are heavily reliant on good yield potential estimates. Yet, the prediction from GAEZ, appear to be in some ways in contradiction with field observations at a European scale. This constitute a major limitation of this work. The extensive use of background datasets, especially in modelling irrigation also limits the spatial resolution of the results. Finally, because soil organic carbon were treated independently, the analysis of the environmental performance remains incomplete.

Future work can extend on this study by incorporating a better SOC change estimate that would account for both the importance of site specific variable and the singularities of each crops. Refining the spatial variability of the inventory, especially regarding the irrigation process would also greatly increase the accuracy of the results. Finally, future work should focus on better modelling the spatial dependency of biomass production on nitrogen fertilizer requirements.

5 References

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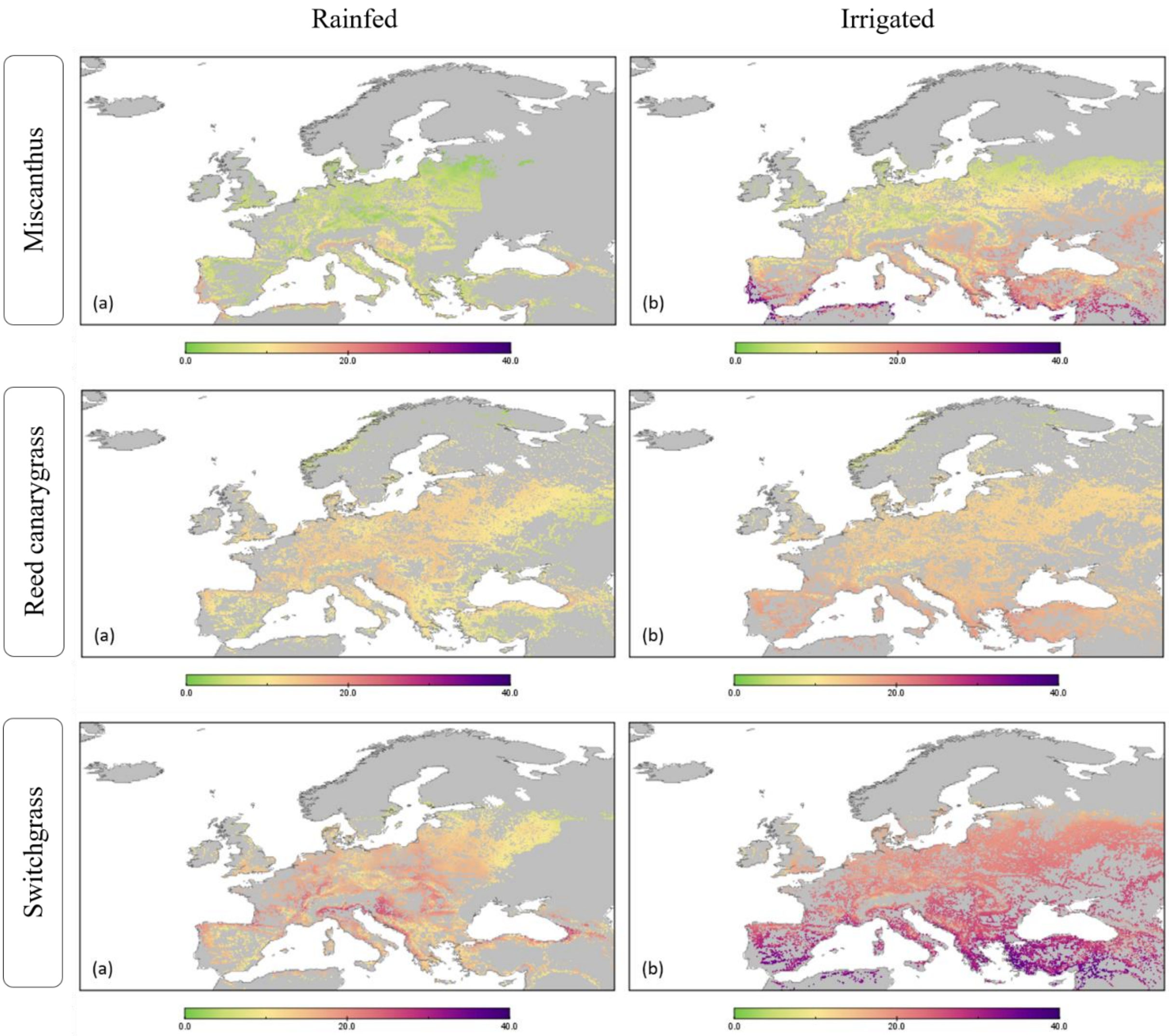
6 Appendices

Appendix 1: Modelled maximum agro-climatic harvested yield of miscanthus, reed canarygrass and switchgrass on abbandonned agricultural lands in 2020 at the end of the growing season under high input management. (a) Potential non-water limited yield and (b) Potential rainfed yield. (tDM/ha).



Appendix 2: Estimates of the lifetime of perennial grasses stand in the literature

Crop	Lifetime (yrs)	Reference
Miscanthus	20-25	[30]
	20	[59, 61, 134, 248, 270, 271]
	19	[93, 272]
	18	[89]
	16.5	[43]
	16	[273, 274]
	>15	[48, 85, 275, 276]
	15	[1, 53, 60, 91, 109, 204, 277]
	10	[92]
Selected value	17	
Reed canarygrass		
	>16	[79]
	>10	[30, 149]
	10	[48, 108, 110]
	3-5	[80]
Selected value	10	
Switchgrass		
	10-20	[82, 120]
	16	[274]
	>15	[83]
	15	[59, 60, 99]
	>10	[84, 278, 279]
	10	[108, 204, 277]
	5-8	[81]
Selected value	15	

Appendix 3: Changes in miscanthus yield between early and late harvest

Field trial location	Variety	Biomass yield (tDM/ha)		Reference
		Peak (Early)	Overwintered (Late)	
Ireland	Giganteus	13.4	9.0	[49]
Europe	3 varieties	17.0	14.0	[148]
UK	Giganteus	8.8	6.1	[89]
Germany	Giganteus	25.7	14.5	[141]
UK	Giganteus	21.3	15.0	[198]
France	Giganteus	22.8	16.9	[186]
France	Giganteus	28.0	20.0	[147]
Turkey	Giganteus	20.8	18.1	[97]

Early harvest corresponds to harvest at peak standing biomass, usually in autumn in Europe [49, 148]. Late harvest time ranges across climate from winter [147, 159] to early spring following complete senescence of the crop [49, 161].
Values were collected from text, tables and figures in studies reporting biomass yields measurement and estimates.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 4: Miscanthus biomass loss from delayed harvest

Field trial location	Variety	Yield reduction from delayed harvest (% peak yield)	Reference
Ireland	Giganteus	33	[49]
Europe	3 varieties	35	[148]
Germany	Giganteus	25	[183]
UK	Giganteus	31	[89]
Germany	Giganteus	44	[141]
UK	Giganteus	30	[198]
France	Giganteus	26	[186]
France	Giganteus	29	[147]
Turkey	Giganteus	13	[97]
Word	Giganteus	28	[77]
Germany	Giganteus	26	[170]
Italy	Giganteus	36	[182]
Netherland	Giganteus	34	[93]
Average		30%	
Selected value for this work		30%	

Early harvest corresponds to harvest at peak standing biomass, usually in autumn in Europe [49, 148]. Late harvest time ranges across climate from winter [147, 159] to early spring following complete senescence of the crop [49, 161].
Values were collected from text, tables and figures in studies reporting overwinter biomass losses or computed from yield values presented in Appendix 3
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 5: Changes in reed canarygrass yield between early and late harvest

Field trial location	Variety	Biomass yield (tDM/ha)			Reference
		Peak (Early)	Autumn	Overwintered (Late)	
Estonia	3 varieties	8.6	-	6.8	[157]
USA, WS	-	7.1	-	5.5	[163]
Sweden	Palaton	9.3	-	7.4	[190]
Czech republic	-	8.1	-	5.4	[162]
Czech republic	-	8.4	8.0	6.0	[155]
USA, IA, WI	7 varieties	-	5.9	3.0	[46]
Sweden	Palaton, Venture	9.7	-	6.7	[131]

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from July [155] to late fall [157].
Autumn harvest occurs when crops have started to senesce, usually following killing frost.
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [159, 160] to early spring [162].
Values were collected from text, tables and figures in studies reporting biomass yields measurement and estimates.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 6: Reed canarygrass biomass loss from delayed harvest

Field trial location	Variety	Yield reduction from delaying harvest			Reference
		Autumn (% peak)	Late (% autumn)	Late (% peak)	
Estonia	3 varieties	-	-	21	[157]
USA, WS	-	-	-	26	[163]
Sweden	Palaton	-	-	20	[190]
Czech republic	-	-	-	33	[162]
Czech republic	-	5	24	28	[155]
USA, IA, WI	7 varieties	-	49	-	[46]
Europe	-	-	-	25%	[280]
Sweden	-	-	-	30	[145]
Average		5%	35%	26%	
Selected value for this work				26%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from July [155] to late fall [157].
Autumn harvest occurs when crops have started to senesce, usually following killing frost.
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [159, 160] to early spring [162].
Values were collected from text, tables and figures in studies reporting overwinter biomass losses or computed from yield values presented in

Appendix 5*Appendix 5*

Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 7: Changes in switchgrass yield between early and late harvest

Field trial location	Variety	Biomass yield (tDM/ha)			Reference
		Peak (Early)	Autumn	Overwintered (Late)	
USA, MA	CIR	6.3	-	5.1	[156]
Turkey	Alamo	-	19.0	17.1	[97]
USA, IA	CIR	8.6	6.7	4.2	[281]
USA, NB	CIR	11.8	10.3	-	[195]
USA, PA	3 varieties	8.9	7.0	4.4	[143]
USA, MA	1CIR	10.8	7.8	-	[158]
USA, IL	CIR	10.0	7.3	5.9	[173]
USA, IL	6 varieties	11.4	9.1	6.8	[196]
USA, OK	Kanlow	7.9	-	6.7	[197]

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from late summer[156] to fall[158]
Autumn harvest occurs when crops have started to senesce, usually following killing frost [128, 156].
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [160] to early spring [159].
Values were collected from text, tables and figures in studies reporting biomass yields measurement and estimates.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 8: Switchgrass biomass loss from delayed harvest

Field trial location	Variety	Yield reduction from delaying harvest	Reference
		Late harvest (% peak yield)	
USA, MA	CIR	19	[156]
USA; IA	-	51	[281]
USA, PA	3 varieties	51	[143]
USA, IL	CIR	41	[173]
USA, IL	3 varieties	32	[196]
USA, OK	Kanlow	15	[197]
USA, AK	Alamo	29	[128]
USA, WS	-	17	[163]
Average		32%	
Selected value for this work		32%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from late summer[156] to fall[158]
Autumn harvest occurs when crops have started to senesce, usually following killing frost [128, 156].
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [160] to early spring [159].
Values were collected from text, tables and figures in studies reporting overwinter biomass losses or computed from yield values presented in Appendix 7.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 9: Moisture content of miscanthus biomass at different harvest time

Field trial location	**Variety**	**Moisture content (%)**		**Reference**
		Peak (Early)	**Overwintered (Late)**	
Ireland	Giganteus	58	40	[49]
Europe	3 varieties	56	30	[148]
Germany	Giganteus	56	30	[141]
Spain	Giganteus	-	22	[159]
UK	Giganteus	67	46	[198]
Italy	Giganteus	46	-	[47]
Turkey	Giganteus	44	22	[97]
Poland	Giganteus	34	15	[161]
UK	Giganteus	60	26	[199]
Germany	2 varieties	71	19	[200]
Italy	Giganteus	52	13	[137]
Average		54%	26%	
Selected value for this work		54%	26%	

Early harvest corresponds to harvest at peak standing biomass, usually in autumn in Europe [148]. Late harvest time ranges across climate from winter [147, 159] to early spring following complete senescence of the crop [49, 161].
Values were collected from text, tables and figures in studies reporting moisture content of standing or harvested biomass. Moisture content from biomass harvested in two steps were excluded due to the potential decrease in moisture content from field drying.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 10: Moisture content of reed canarygrass biomass at different harvest time

Field trial location	Variety	Moisture content (%)			Reference
		Peak (Early)	Autumn	Overwintered (Late)	
UK	Palaton	-	-	5	[160]
USA, WS	-	52	-	-	[163]
USA, WS	-	-	46	15	[88]
Sweden	Palaton	60	55	15	[190]
Czech republic	-	44	-	14	[162]
Czech republic	-	64	45	22	[155]
USA, IA,WI	7 varieties	-	41	16	[46]
Average		55%	47%	16%	
Selected value for this work		55%		16%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from July [155] to late fall [157].
Autumn harvest occurs when crops have started to senesce, usually following killing frost.
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [159, 160] to early spring [162].
Values were collected from text, tables and figures in studies reporting moisture content of standing or harvested biomass. Moisture content from biomass harvested in two steps were excluded due to the potential decrease in moisture content from field drying.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 11: Moisture content of switchgrass biomass at different harvest time

Field trial location	Variety	Moisture content (%)			Reference
		Peak (Early)	Autumn	Overwintered (Late)	
Italy	Alamo	-	-	23	[201]
USA, PA	3 varieties	-	35	7	[143]
Italy	Alamo	57	-	-	[137]
USA, MA	CIR	62	40	14	[156]
Turkey	Alamo	-	47	24	[97]
Spain	CIR, Alamo, Kanlow	-	-	33	[159]
UK	CIR	-	-	5	[160]
USA, MA	CIR	49	29	-	[158]
USA, IL	CIR	56	24	14	[173]
USA, AR	Alamo	52	35	20	[128]
USA, WS	-	66	-	-	[163]
USA, WS	-	-	44	18	[88]
Italy	Alamo	-	-	16	[168]
Average		57%	36%	17%	
Selected value for this work		57%		17%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from late summer[156] to fall[158]
Autumn harvest occurs when crops have started to senesce, usually following killing frost [128, 156].
Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [160] to early spring [159].
Values were collected from text, tables and figures in studies reporting moisture content of standing or harvested biomass.
Moisture content from biomass harvested in two steps were excluded due to the potential decrease in moisture content from field drying.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 12: Miscanthus nutrient concentration - early harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
Italy	Giganteus	0.50	0.075	0.70	[182]
Germany	Giganteus	0.36	0.12	1.1	[183]
Italy	Giganteus	0.60	0.15	-	[184]
UK	Giganteus	0.50	0.069	1.2	[185]
UK	Giganteus	0.70	0.10	0.53	[49]
Europe	3 varieties	0.50	-	0.89	[148]
Germany	Giganteus	0.47	0.090	1.1	[59]
Germany	Giganteus	0.55	0.10	0.75	[141]
France	Giganteus	0.44	-	-	[186]
Germany	Giganteus	0.72	0.11	1.5	[170]
France	Giganteus	0.42	-	-	[147]
Average		0.52%	0.10%	0.97%	
Selected value for this work		0.52%	0.10%	0.97%	

Early harvest corresponds to harvest at peak standing biomass, usually in autumn in Europe [148].
Values were collected from text, tables and figures in studies reporting biomass content at peak biomass standing.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 13: Miscanthus nutrient concentration - late harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
Italy	Giganteus	0.16	0.045	0.39	[182]
Germany	Giganteus	0.13	0.075	0.63	[183]
UK	Giganteus	0.50	0.063	1.2	[185]
Spain	Giganteus	0.24	0.023	0.16	[159]
UK	Giganteus	0.40	0.060	0.39	[49]
UK	Giganteus	0.40	-	-	[109]
Europe	3 varieties	0.40	-	0.42	[148]
Germany	Giganteus	0.35	0.070	0.40	[141]
France	Giganteus	0.19	-	-	[186]
Italy	Giganteus	0.21		-	[187]
France	Giganteus	0.21	-	-	[147]
Germany	Giganteus	0.44	0.070	0.82	[170]
Average		0.30%	0.058%	0.55%	
Selected value for this work		0.30%	0.058%	0.55%	

Late harvest time ranges across climate from winter [147, 159] to early spring following complete senescence of the crop [49, 161].
Values were collected from text, tables and figures in studies reporting biomass content following overwintering of the biomass.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 14: Reed canarygrass nutrient concentration - early harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
Sweden	Palaton	1.33	0.17	1.23	[192]
Poland	Bamse	0.98	0.065	0.35	[191]
USA, IA, WI	7 varieties	0.83	-	-	[46]
Sweden	-	0.94	0.19	2.17	[131]
Sweden	Palaton	1.33	0.17	1.23	[48]
Estonia	Palaton	0.77	-	-	[157]
Latvia	-	0.93	0.16	0.76	[112]
Canada, QC	Bellevue	1.1	-	1.5	[189]
Czech republic	-	1.0	0.17	057	[162]
Czech republic	-	0.92	0.22	0.51	[155]
Sweden	-	0.98[a]	0.14[a]	0.93[a]	[190]
Average		1.0%	0.16%	1.0%	
Selected value for this work		1.0%	0.16%	1.0%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from July [155] to late fall [157].
Values were collected from text, tables and figures in studies reporting biomass content at peak biomass standing.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.
[a] Data for northern Sweden are excluded due to the singularity of the boreal climate and the low contribution from high latitudes to the total cropped area considered in this study (as identified in Figure 1)

Appendix 15: Reed canarygrass nutrient concentration - late harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
UK	13 varieties	0.70	0.05	0.19	[36]
Sweden	Palaton	0.88	0.11	0.27	[192]
Sweden	Bamse	-	0.12	0.23	[117]
UK	Palaton	0.26	0.0	0.14	[160]
USA, IA	7 varieties	0.65	-	-	[46]
Sweden	Palaton	0.88	0.11	0.27	[48]
Sweden	-	0.61	0.090	0.16	[131]
Czech republic	-	0.92	0.14	0.14	[162]
Czech republic	-	0.73	0.20	0.16	[155]
Estonia	Palaton	0.66	-	-	[157]
Sweden	-	0.80	0.050	0.15	[190]
Average		0.71%	0.097%	0.19%	
Selected value for this work		0.71%	0.097%	0.19%	

Late harvest corresponds to harvest after complete senescence. It ranges from late winter [159, 160] to early spring [162]. or locations. For one study, multiple values follow the same order across column (ie: the earliest observation is given first and the latest observation is given last)
Values were collected from text, tables and figures in studies reporting biomass content following overwintering of the biomass.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 16: Switchgrass nutrient concentration - early harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
USA, OK	31 varieties	0.93	0.13	0.80	[193]
USA, IA	CIR	0.75	-	-	[281]
USA, NB	CIR	0.96	-	-	[195]
USA, MA	CIR	0.6	0.17	0.16	[156]
USA, IL	6 varieties	0.917	0.24	0.82	[196]
USA, OK	Kanlow	0.43	0.11	0.50	[197]
Average		0.77%	0.17%	0.57%	
Selected value for this work		0.77%	0.17%	0.57%	

Early harvest corresponds to harvest at peak standing biomass. Early harvest time ranges across climate from late summer[156] to fall[158]
Values were collected from text, tables and figures in studies reporting biomass content at peak biomass standing.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 17: Switchgrass nutrient concentration - late harvest

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
USA, IA	CIR	0.30	-	-	[281]
USA, MA	CIR	0.24	0.030	0.040	[156]
USA, AR	Alamo	0.4	-	-	[33]
USA, IL	6 varieties	0.44	0.05	0.1	[196]
USA, OK	Kanlow	0.32	0.05	0.080	[197]
USA, PA	3 varieties	0.41	0.041	0.060	[143]
Spain	CIR, Alamo, Kanlow	0.32	0.052	0.23	[159]
Average		0.35%	0.045%	0.10%	
Selected value for this work		0.35%	0.045%	0.10%	

Late harvest corresponds to harvest after complete senescence of the crop. It ranges from late winter [160] to early spring [159].
Values were collected from text, tables and figures in studies reporting biomass content following overwintering of the biomass.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 18: Reed canarygrass nutrient concentration – harvest at killing frost

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
UK	13 varieties	0.77	0.06	0.40	[36]
UK	Advanta	0.80	-	-	[109]
Canada, QC	Bellevue	0.88	0.21	0.75	[189]
Average		0.82%	0.14%	0.58%	
Selected value for this work		0.45%	0.07%	0.26%	

Autumn harvest occurs when crops have started to senesce, usually following killing frost.
Values were collected from text, tables and figures in studies reporting biomass content in autumn following killing frost.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 19: Switchgrass nutrient concentration - harvest at killing frost

Field trial location	Variety	Nutrient content (% DM)			Reference
		Nitrogen	Phosphorus	Potassium	
USA, OK	31 varieties	0.54	0.055	0.25	[193]
USA, OK	Alamo	0.53	0.09	0.57	[205]
UK	7 varieties	0.57	0.049	0.18	[130]
USA, MA	CIR	0.46	0.086	0.34	[143]
USA, MA	CIR	0.53	-	-	[195]
USA, AR	Alamo	0.39	-	-	[281]
USA, IL	6 varieties	0.39	-	-	[225]
USA, OK	Kanlow	0.54	-	-	[224]
Spain	Alamo	0.51	-	-	[104]
Spain	CIR, Alamo, Kanlow	0.42	0.05	0.09	[160]
Canada, ON	CIR, Sunburst	0.41	0.066	0.25	[32]
USA, OK	Kanlow	0.33	0.080	0.26	[197]
USA, MA	CIR	0.26	0.090	0.12	[156]
Average		0.45%	0.07%	0.26%	
Selected value for this work		0.45%	0.07%	0.26%	

Autumn harvest occurs when crops have started to senesce, usually following killing frost [128, 156].
Values were collected from text, tables and figures in studies reporting biomass content in autumn following killing frost.
Reported values for each study are average across fields, years of observation, fertilization treatments, irrigation levels and varieties.
Data were only collected for field older than 1 year.
- Indicates missing information.

Appendix 20: Diesel consumption - establishment operations

Operation	Diesel consumption ($l.ha^{-1}$)	Data type					Reference
		Field measurement				Model	
		MSC	RCG	SWG	Other		
Ploughing	24.6 – (22.0-26.0)	•					[53, 98, 110, 135]
	22.0			•			[254]
	25.2					•	[204]
	21.8 – (15.0-30.0)				L		[250]
	23.0 – (15.0-40.0)				L		[251]
	24.8				L		[252]
	23.2						[250-252]
Harrowing	12.7 – (12.4-13.0)	•					[53, 93]
	6.6					•	[204]
	17.9				L		[252]
	14.5 – (11.9-18.2)				L		[253]
	12.7 – (8-22)				L		[250]
	10.0				L		[251]
	13.8						[250-253]
Cultivating – Spring tine	9.7		•				[110]
	5.0 – (4.8-5.3)					•	[93]
	6.0				L		[251]
	9.3 – (8.3-10.6)				L		[253]
	7.7						[251, 253]
Planting – Potato planter	16.8 – (11.7-30)	•					[50, 53, 98, 135]
	17.5 – (15-20)				L		[251]
	16.8						[50, 53, 98, 135]
Planting – Seed drill	3.7		•				[110]
	4.7			•			[254]
	5.0				L		[251]
	8.3				L		[252]
	4.2						[110, 254]
Rolling	4.8 – (3.1-6.5)			•			[136, 254]
	2.0		•				[110]
	2.9	•					[53]
	3.5				L		[251]
	3.5						[251]
Fertilizer application	1.7 – (1.1-2.3)	•					[98, 249]
	2.8		•				[110]
	2.2				L		[250]
	1.5				L		[251]
	1.9						[250, 251]
Lime application	2.5		•				[110]
	2.5				L		[251]
	2.5						[110, 251]

Operation	Diesel consumption (l.ha-1)	Data type: Field measurement: MSC	RCG	SWG	Other	Model	Reference
Weeding	1.2			•			[50]
	1.1 – (0.8-1.3)	•					[53, 90, 249]
	2.4 – (1.5-3.3)		•				[104, 110]
	2.0				L		[250]
	2.0				L		[251]
	2.0						[250, 251]
Topping – MSC	7.0					•	[96]
	6.4	•					[249]
	6.4						[249]

Average Diesel consumption from different field operation. Ranges displayed in brackets if available.
Values selected for this study appear in bold.
Diesel consumption values were taken from literature sources both specific and non-specific to perennial grasses.
Values found in the literature are either taken from field measurement or computed using Diesel consumption models.
L: Large scale studies, looking at different types of soil over a large number of field measurement

Appendix 21: Diesel consumption - cutting operations

	Diesel consumption: $l.h^{-1}$	$l.ha^{-1}$	$l.tDM^{-1}$	Throughput $tDM.h^{-1}$	Yield $tDM.ha^{-1}$	Field	Model	Reference
Miscanthus	19.5	10.0	1.2	15.9	8.2	•		[51]
	33.7	18.4	1.5	39.3	12.6	•		[166]
	61.2	21.5	1.7	25.9	12.6	•		[166]
	31.0	15.0	0.8	37.6	18.2	•		[255]
	-	16.0	2.0	-	8.0	•		[135]
	-	19.2	1.0	31.2	19.1	•		[167]
	55.0	30.6	2.1	26.4	14.7		•	[53]
	45.0	19.6	1.3	33.7	14.7		•	[53]
	-	28.2	1.9	-	15.0		•	[50]
	-	33.6	2.2	-	15.0		•	[50]
	-	32.7	1.4	22.6	23.5		•	[54]
			1.4					[51, 135, 166, 167, 255]
Switchgrass – Reed canarygrass	0.7	5.0	0.3	-	16.7	•		[104]
	-	5.1	-	-	-	•		[136]
	-	-	1.0	-	-		•	[204]
	12.4	6.2	1.0	-	6.0	•		[110]
			1.0					[110, 204]

Values selected for this study appear in bold.
Diesel consumption values were collected from relevant studies on perennial grasses.
Miscanthus is usually cut and conditioned using a forage harvester [51, 96] or a self-propelled mower [166, 167]. Values reported here were collected irrespective of the type of machinery.
Switchgrass and reed canarygrass are usually cut using a mower conditioner [104, 110] or a windrower [136]. Conditioning is preferably avoided in late harvest to reduce harvest loss of the brittle overwintered biomass. However, available data did not allow for the distinction and a single Diesel consumption is used for both harvest time.
Diesel consumption per tons of dry mater were computed as the ratio of the Diesel consumption per hour to throughput or as the ratio of the Diesel consumption per hour to yield.
- Indicates missing information.

Appendix 22: Diesel consumption - balling operations

	Diesel consumption			Throughput	Yield	Field	Model	Reference
	l.h^{-1}	**l.ha^{-1}**	**l.tDM^{-1}**	**tDM.h^{-1}**	**tDM.ha^{-1}**	**exp**		
Miscanthus	30.0	23.8	1.2	24.6	19.5	•		[255]
	20.2	17.7	1.4	14.4	12.6	•		[166]
	21.4	15.1	1.2	17.8	12.6	•		[166]
	27.6	19.7	1.1	25.1	18.7	•		[167]
	18.5	-	1.4	13.2	-		•	[60]
	-	19.9	1.3	-	15.0		•	[50]
	-	16.0	1.1	-	15.0		•	[50]
	35.0	14.0	1.0	36.7	14.7		•	[53]
	25.0	10.9	0.7	33.7	14.7		•	[53]
	-	12	1	-	12		•	[282]
			1.2					[166, 167, 255]
Switchgrass – Reed canarygrass	19.88	4.5	1.9	10.7	2.42	•		[169]
	-	-	0.9	27.0	-	•		[88]
	-	-	0.8	24.6	-	•		[88]
	-	-	1.1	31.0	-	•		[88]
	-	-	0.9	22.6	-	•		[88]
	-	-	1.2	32.0	-	•		[136]
	-	-	1.2	21.6	-	•		[136]
	17.1	13.4	1.0	16.8	13.2	•		[201]
	-	-	0.8	23.6	-	•		[88]
	-	-	0.8	24.1	-	•		[88]
	8.6	11.5	1.9	4.5	6.0	•		[110]
	-	-	1.9	-	-		•	[204]
	33.3	-	1.2	27.8	-		•	[169]
			1.1					[88, 110, 136, 169, 201]

Values selected for this study appear in bold.
Diesel consumption values were collected from relevant studies on perennial grasses.
Two types of baller are commonly used for balling operations, large square ballers [88, 166, 169] and round ballers [110, 168, 201]. Values reported here were collected irrespective of the baller type as it was assumed that both types would most likely be used at a European scale.
Diesel consumption per tons of dry mater were computed as the ratio of the Diesel consumption per hour to throughput or as the ratio of the Diesel consumption per hour to yield.
- Indicates missing information.

Appendix 23: Energy consumption - Irrigation

Ecoinvent process	**Diesel consumption (l.m^{-3})**	**Electricity consumption (kWh.m^{-3})**
Irrigation {ES}| processing, U	0.00375	0.24
Irrigation {FR}| processing, U	0.00375	0.24
Irrigation {DE}| processing, U	0.00375	0.24
Irrigation {CH}| processing, U	0.00375	0.73
	0.00375	**0.36**

Values selected for this study appear in bold.
The selected values are computed as the average of the Diesel and electricity consumption of the different Ecoinvent processes.

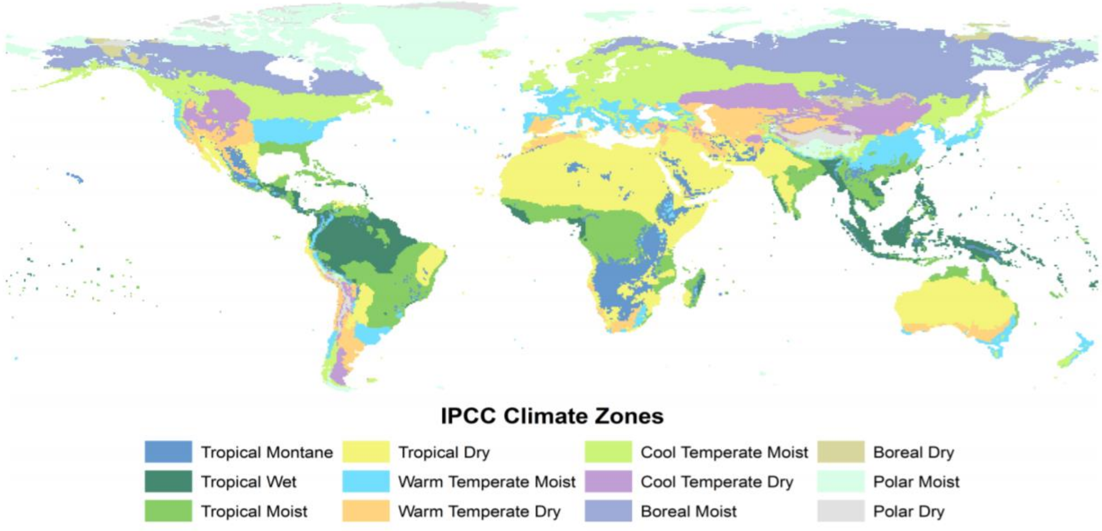
Appendix 24: Average European emission factors used in this work

Factor	Unit	Irrigated		Non irrigated	
		Fertilizer	**Others**	**Fertilizer**	**Others**
EF$_{direct\ N2O}$ ⁑	kg N_2O-N/kg N	0.015	0.006	0.015	0.006
EF$_{indirect\_gas\ N2O}$ ⁑	kg N_2O-N/kg N volatilized	0.0134	-	0.0132	-
Frac$_{leach}$ ⁑	kg NO_3^--N leached/kg N	0.240	0.240	0.225	0.225

Factor	Unit	Constant across irrigation scenarios
Frac$_{gas\ urea}$	kg N volatilized/kg N as urea	0.153
EF$_{indirect\ leach\ N2O}$	kg N_2O-N/kg N leached-runoff	0.011
P$_{runoff\ fertilizer}$	kg PO_4^{3-}-P/kg P_2O_5 applied	0.001
EF$_{NH3\ urea}$	kg NH_3-N/kg N as urea	0.142
EF$_{NO2\ urea}$	kg NO_2-N/kg N as urea	0.011
EF$_{CO2\ urea}$	kg CO_2-C/kg urea	0.200
EF$_{CO2\ lime}$	kg CO_2-C/kg lime	0.120
P$_{runoff\ land}$	kg PO_4^{3-}-P/ha.yr	0.25
P$_{leach\ land}$	kg PO_4^{3-}-P/ha.yr	0.06
NMVOC$_{land}$	kg NMVOC/ha.yr	0.86
PM10$_{land}$	kg PM10/ha.yr	1.56
PM2.5$_{land}$	kg PM2.5/ha.yr	0.06

Emission factors assumed constant across Europe, crop and harvest scenario.
⁑ Emission factors for irrigated and rainfed conditions were obtained from dry and wet climate emission factors as found in [231] (reported in Appendix 26) European average emission factors for irrigated and rainfed conditions are obtained assuming that 6% of the European area has a dry climate while the 94% remaining have a wet climate. The rational for this assumption is that Spain and Greece (accounting for 6% of the European area) are the main countries that have a dry climate according to the IPCC climate zone classification (Appendix 25).
All other factors assumed constant across irrigation scenarios.
Converting CO_2-C to CO_2: factor 44/12
Converting NO_3^--N to NO_3^-: factor 62/14
Converting PO_4^{3-}-P to PO_4^{3-}: factor 95/31
Converting N_2O-N to N_2O: factor 44/28
Converting NO_2-N to NO_2: factor 46/14
Converting NH_3-N to NH_3: factor 17/14

Appendix 25: Delineation of major climate zones



Map from the Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [236]

Appendix 26: Emission factors as found in the IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

	$Freac_{leach}$ (kg N leached/kg N)			
	Dry		**Wet**	
	irrigated	**non irrigated**	**irrigated**	**non irrigated**
Fertilizer	0.24	0	0.24	0.24
Other	0.24	0	0.24	0.24
	$EF_{indirect\ gas\ N2O}$ (kg N_2O -N/kg N volatilized)			
Fertilizer	0.004	0.001	0.014	0.014
Other	0	0	0	0
	$EF_{direct\ N2O}$ (kg N_2O-N/kg N)			
Fertilizer	0.004	0.001	0.016	0.016
Other	0.004	0.001	0.006	0.006

Emission factors as found in:
- Annex 11A.2 Estimation of Default Emission Factor(s) for EF1[231]
- 11.2.2.3 CHOICE OF ACTIVITY DATA – Table 11.3 [231]

Appendix 27: Ecoinvent processes used in this inventory

Operation modelled	Ecoinvent process used ‡	Modification and comments
Mowing	Mowing, by rotary mower {CH}| processing | Cut-off, U	Diesel changed from CH to RER
Spraying	Application of plant protection product, by field sprayer {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 1.76 kg/ha to 1.62 kg/ha. Emission from diesel burning modified by multiplying with 0.92 (=1.62/1.76)
Ploughing	tillage, ploughing {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 26.1 kg/ha to 19.5 kg/ha. Emission from diesel burning modified by multiplying with 0.75 (=19.5/26.1)
Liming	Fertilising, by broadcaster {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 5.29 kg/ha to 2.01 kg/ha. Emission from diesel burning modified by multiplying with 0.37 (=2.1/5.29)
Harrowing	tillage, harrowing, by rotary harrow CH| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 11.5 kg/ha to 11.6 kg/ha. Emission from diesel burning modified by multiplying with 1.0065 (=11.6/11.5)
Cultivating	Tillage, harrowing, by spring tine harrow {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 4.44 kg/ha to 5.88 kg/ha. Emission from diesel burning modified by multiplying with 1.32 (=5.88/4.44)
Rolling	Tillage, rolling {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 3.18 kg/ha to 2.94 kg/ha Emission from diesel burning modified by multiplying with 0.93 (=2.94/3.18)
Planting – MSC	Potato planting {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 8.9 kg/ha to 14.1 kg/ha. Emission from diesel burning modified by multiplying with 1.58 (=14.1/8.9)
Planting – SWG/RCG	Sowing {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 3.82 kg/ha to 3.55 kg/ha Emission from diesel burning modified by multiplying with 0.93 (=3.55/3.82)
Fertilizer application	Fertilising, by broadcaster {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 5.29 kg/ha to 1.56 kg/ha. Emission from diesel burning modified by multiplying with 0.29 (=1.56/5.29)
Topping	Mowing, by rotary mower {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 4.31kg/ha to 5.37kg/ha. Emission from diesel burning modified by multiplying with 1.25 (=5.37/4.31)
Clipping	Mowing, by rotary mower {CH}| processing | Cut-off, U	Diesel changed from CH to RER
Cutting - MSC	Combine harvesting {CH}| processing | Cut-off, U	Machinery use and diesel use were disaggregated. For one year and one hectare or miscanthus cultivation, cutting machinery is used for 0.94 ha (=16/17) which accounts for the absence of harvest during the first year. Fuel consumption however is computed based on yields (1.15 kg /tDM), emission updated by multiplying all previous emissions (associated with 33.3l/ha) with 0.0345 (=1.15/33.3).

Operation modelled	Ecoinvent process used ‡	Modification and comments
Cutting - RCG	Mowing, by rotary mower {CH}| processing | Cut-off, U	Machinery use and diesel use were disaggregated. For one year and one hectare or miscanthus cultivation, cutting machinery is used for 0.9 ha (=9/10) which accounts for the absence of harvest during the first year. Fuel consumption however is computed based on yields (0.87 kg /tDM), emission updated by multiplying all previous emissions (associated with 4.31/ha) with 0.2 (=0.87/4.31).
Cutting - SWG	Mowing, by rotary mower {CH}| processing | Cut-off, U	Machinery use and diesel use were disaggregated. For one year and one hectare or miscanthus cultivation, cutting machinery is used for 0.93 ha (=14/15) which accounts for the absence of harvest during the first year. Fuel consumption however is computed based on yields (0.87 kg /tDM), emission updated by multiplying all previous emissions (associated with 4.31/ha) with 0.2 (=0.87/4.31).
Swathing	Swath, by rotary windrower {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 2.94 kg/ha to 3.36 kg/ha. Emission from diesel burning modified by multiplying with 1.14 (=3.36/2.94)
Baling - MSC	Baling {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 0.743 kg/bale to 0.174kg/bale. Emission from diesel burning modified by multiplying with 0.23 (=0.174/0.743) All other inputs multiplied by 0.23 to account for the difference between silage bale and Hay bales. For details see footnote for Tab. 14.7 [220]
Baling – RCG/SWG	Baling {CH}| processing | Cut-off, U	Diesel changed from CH to RER, Fuel consumption changed from 0.743 kg/bale to 0.161kg/bale. Emission from diesel burning modified by multiplying with 0.22 (=0.161/0.743) All other inputs multiplied by 0.23 to account for the difference between silage bale and Hay bales. For details see footnote for Tab. 14.7 [220]
Bale loading	Bale loading {CH}| processing | Cut-off, U	Diesel changed from CH to RER
Irrigation	Irrigation {CH}| processing Irrigation {ES}| processing Irrigation {FR}| processing Irrigation {DE}| processing	Average European process created from the four processes already existing fro European countries. Multiplying factor for each one of them is assumed to be ¼ (equal contribution). Large differences exist between the electricity consumption required for irrigation in Switzerland and in the three other countries. The differences could not be understood.
Transport of rhizomes	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling {GLO}| transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling | Cut-off, U	Transport distance assumed to be 150 km
Transport of inputs except rhizomes	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Cut-off, U	Transport distance for all inputs assumed to be 150 km

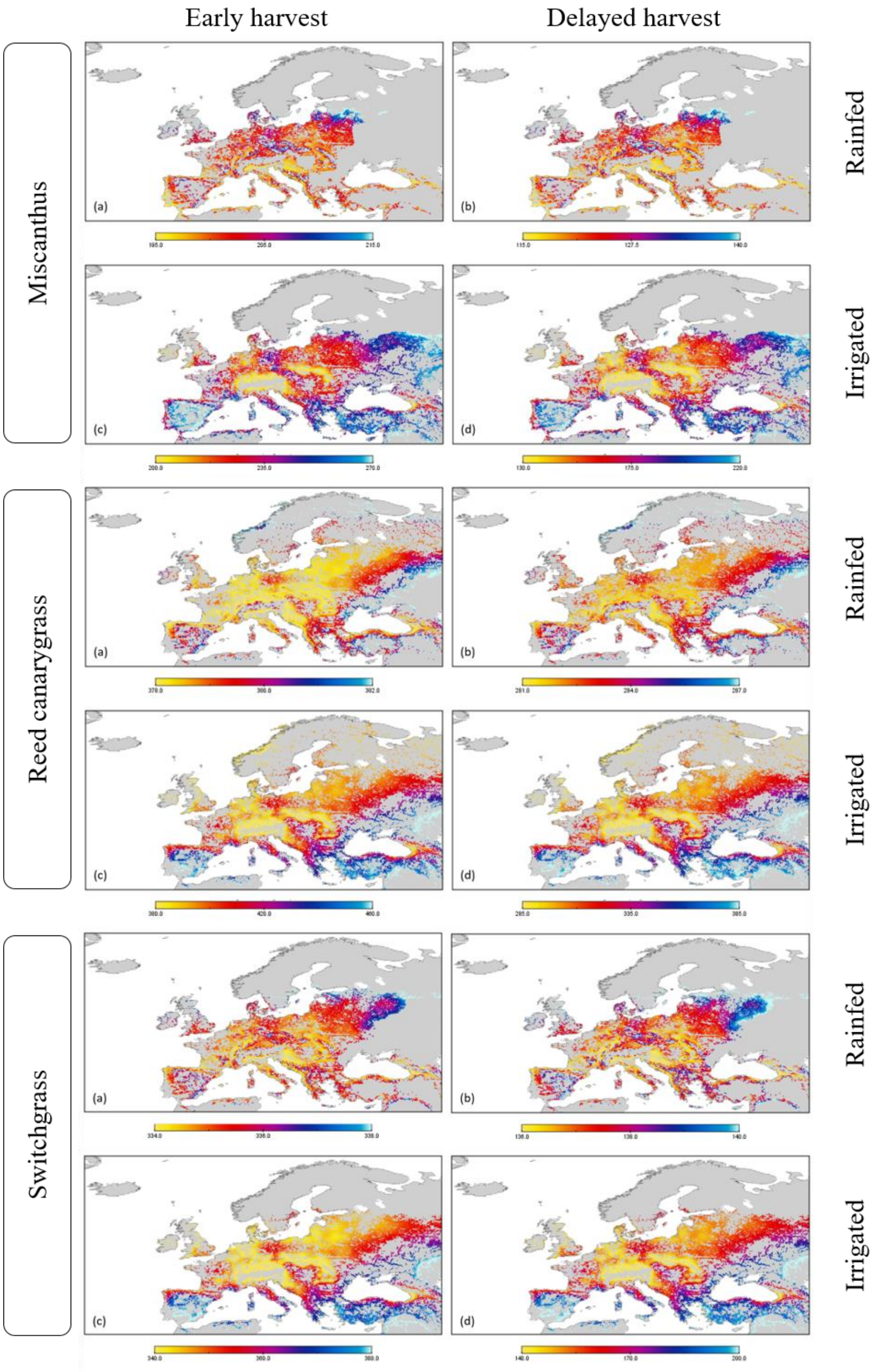
‡ *Ecoinvent processes as found in the Ecoinvent database version 3.0*

Appendix 28: Ecoinvent materials used in this inventory

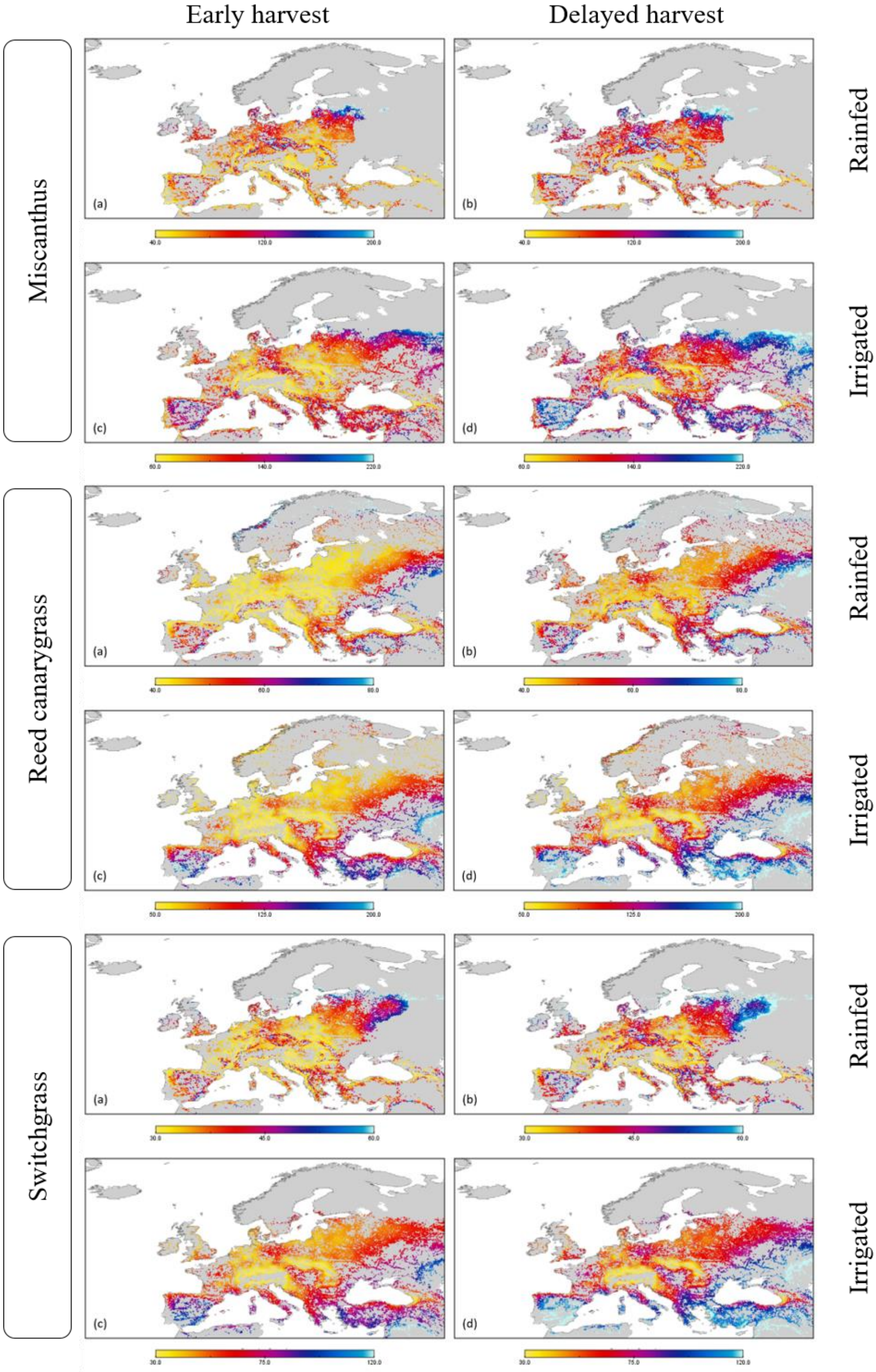
Operation modelled	Ecoinvent material used ‡	Modification and comments
2.4-D	Phenoxy-compound {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Bromoxynil	Nitrile-compound {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Ioxynil	Nitrile-compound {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Dicamba	Benzoic-compound {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Glyphosate	Glyphosate {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Mecoprop-P	Mecoprop {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Nicosulfuron	[sulfonyl]urea-compound {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Pendimethaline	Pendimethalin {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
K2O	Potassium chloride, as K2O {RER}| potassium chloride production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
P2O5	Phosphate fertiliser, as P2O5 {RER}| diammonium phosphate production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Urea	Urea, as N {RER}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27
Miscanthus rhizomes	Miscanthus rhizome, for planting {DE}| production | Cut-off, U	“Market” not available for Europe. “Production” used instead assuming a transport distance of 150 km. Detail on the transport process used are provided in Appendix 27 Electricity consumption for miscanthus rhizome production changed from DE to RER
Switchgrass seeds / reed canarygrass seeds	Grass seed, Swiss integrated production, at farm {GLO}| market for | Cut-off, U	Transport modified from "Transport, freight train {GLO}| market group for | Cut-off, U" to "Transport, freight train {RER}| market group for transport, freight train | Cut-off, U" Transport modified from "Transport, freight, lorry, unspecified {GLO}| market group for transport, freight, lorry, unspecified | Cut-off, U" to "Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U"

‡ *Ecoinvent materials as found in the Ecoinvent database version 3.0*

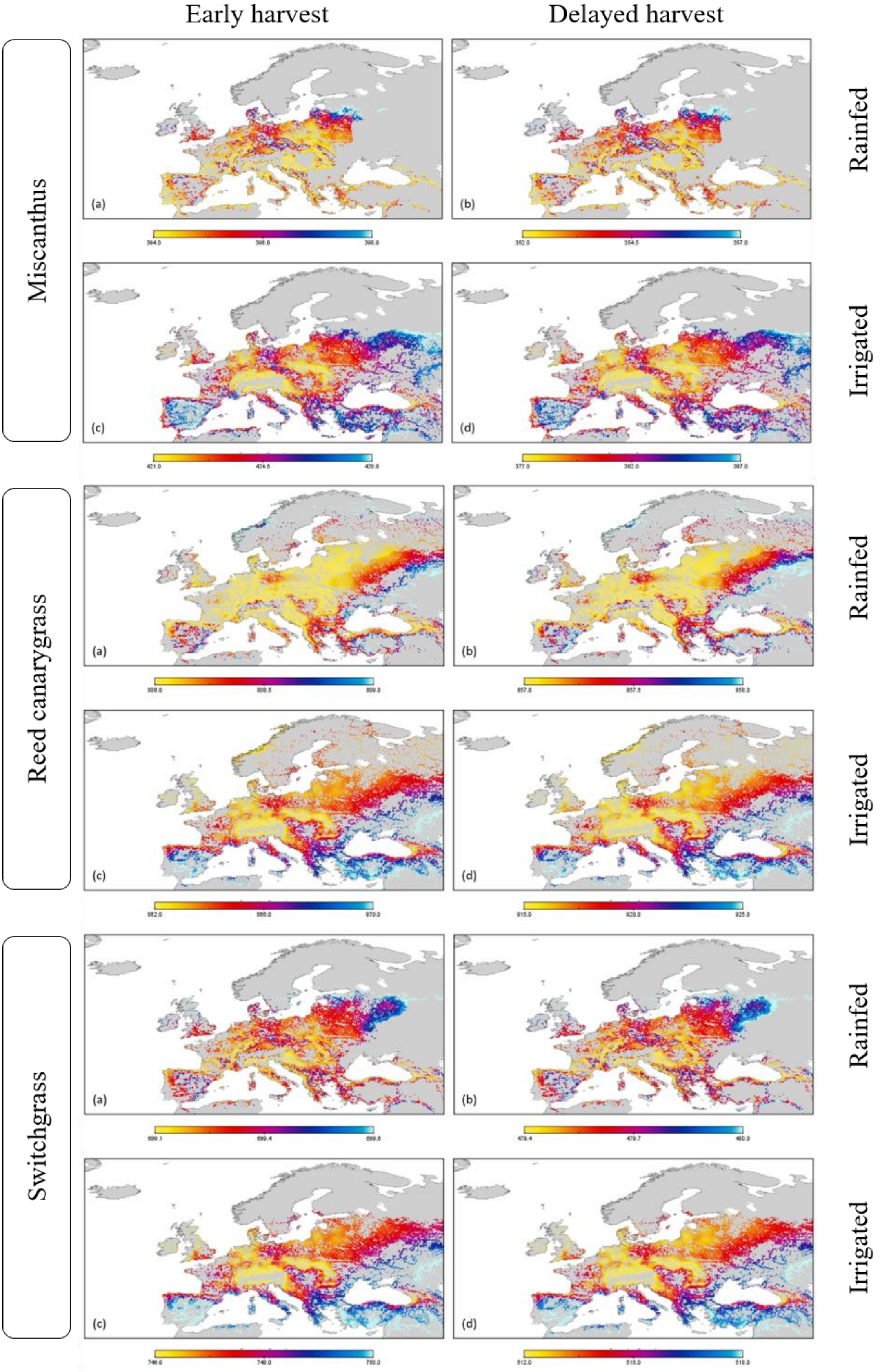
Appendix 29: Life terrestrial acidification impact from the production of 1 tonne of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\,eq}$/tDM) produced. Map scales are based on 5th and 95th percentile and are map-specific.



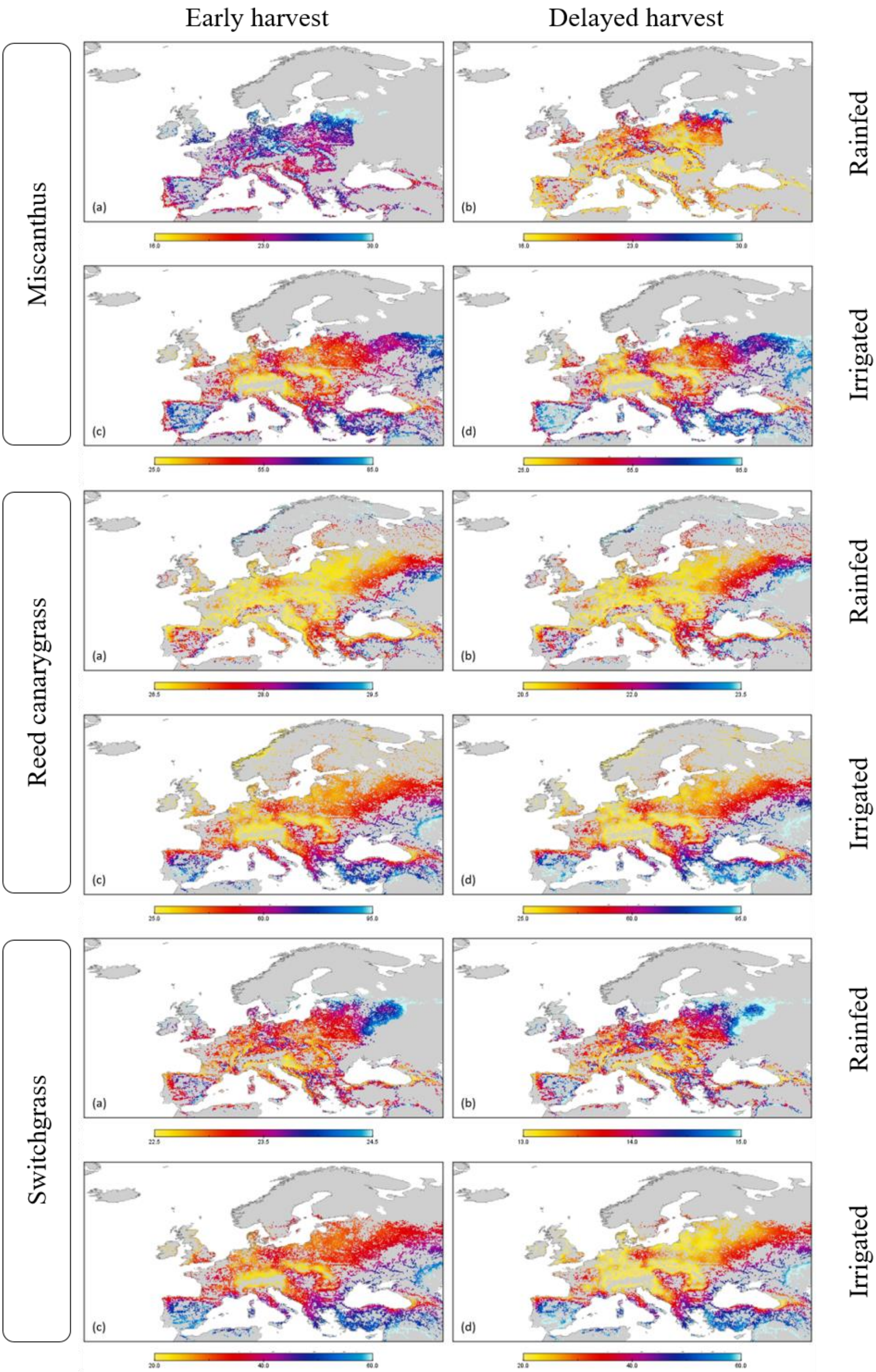
Appendix 30: Life cycle freshwater eutrophication impact from the production of 1 tonne of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\,eq}$/tDM) produced. Map scales are based on 5th and 95th percentile and are map-specific.



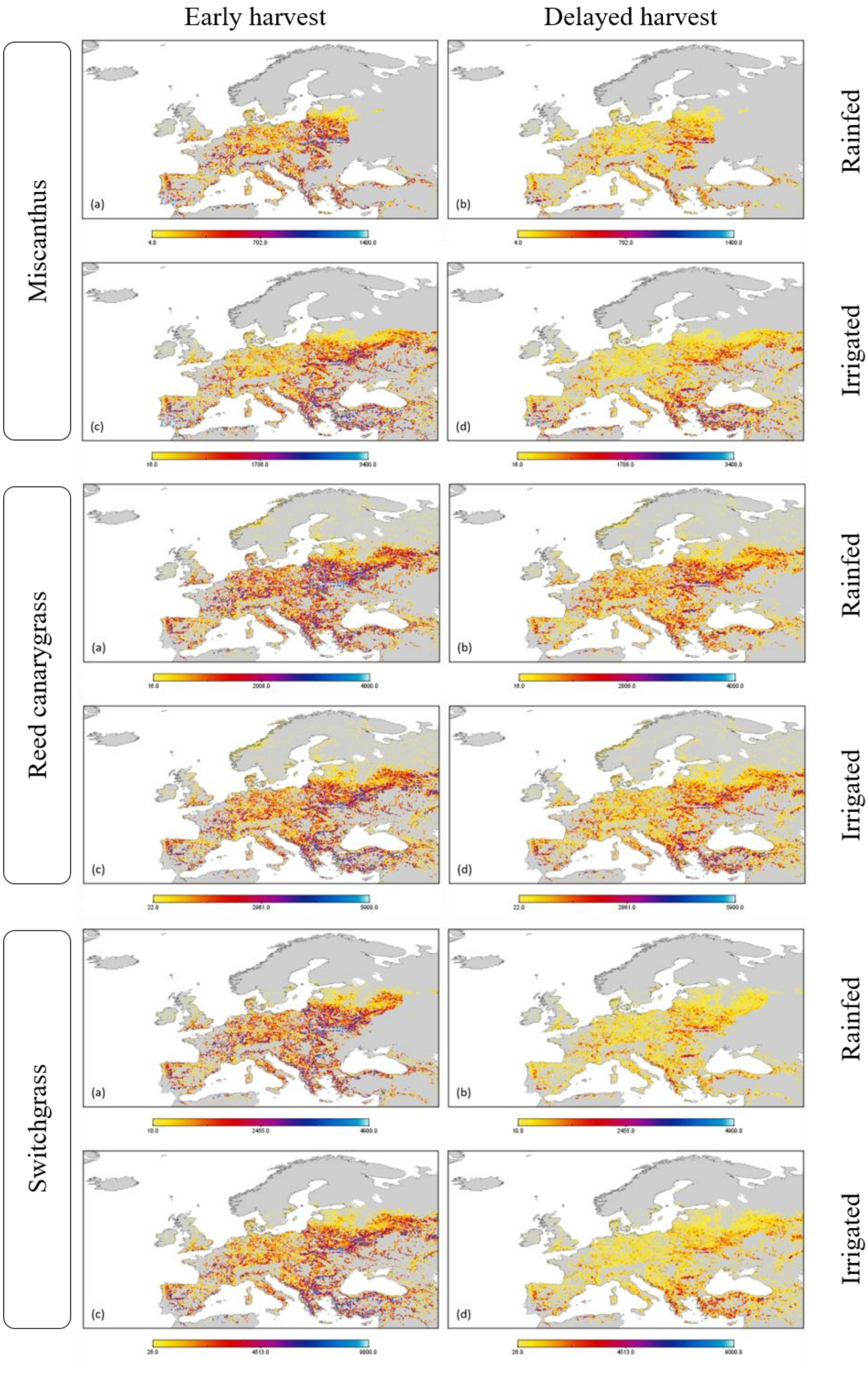
Appendix 31: Life cycle marine eutrophication impact from the production of 1 tonne of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/tDM) produced. Map scales are based on 5th and 95th percentile and are map-specific.



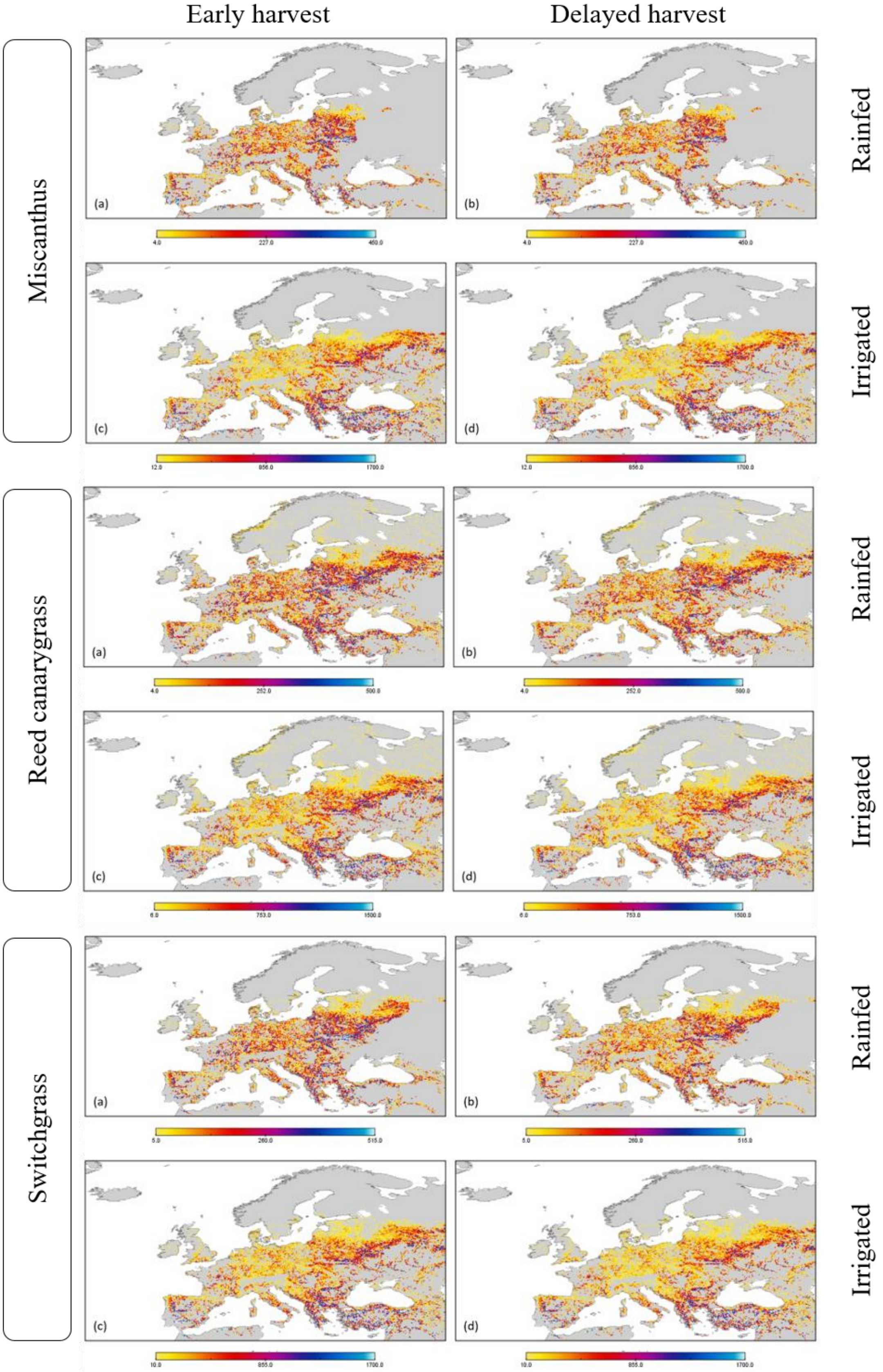
Appendix 32: Life cycle fossil ressource scarcity impact from the production of 1 tonne of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/tDM) produced. Map scales are based on 5^{th} and 95^{th} percentile and are map-specific.



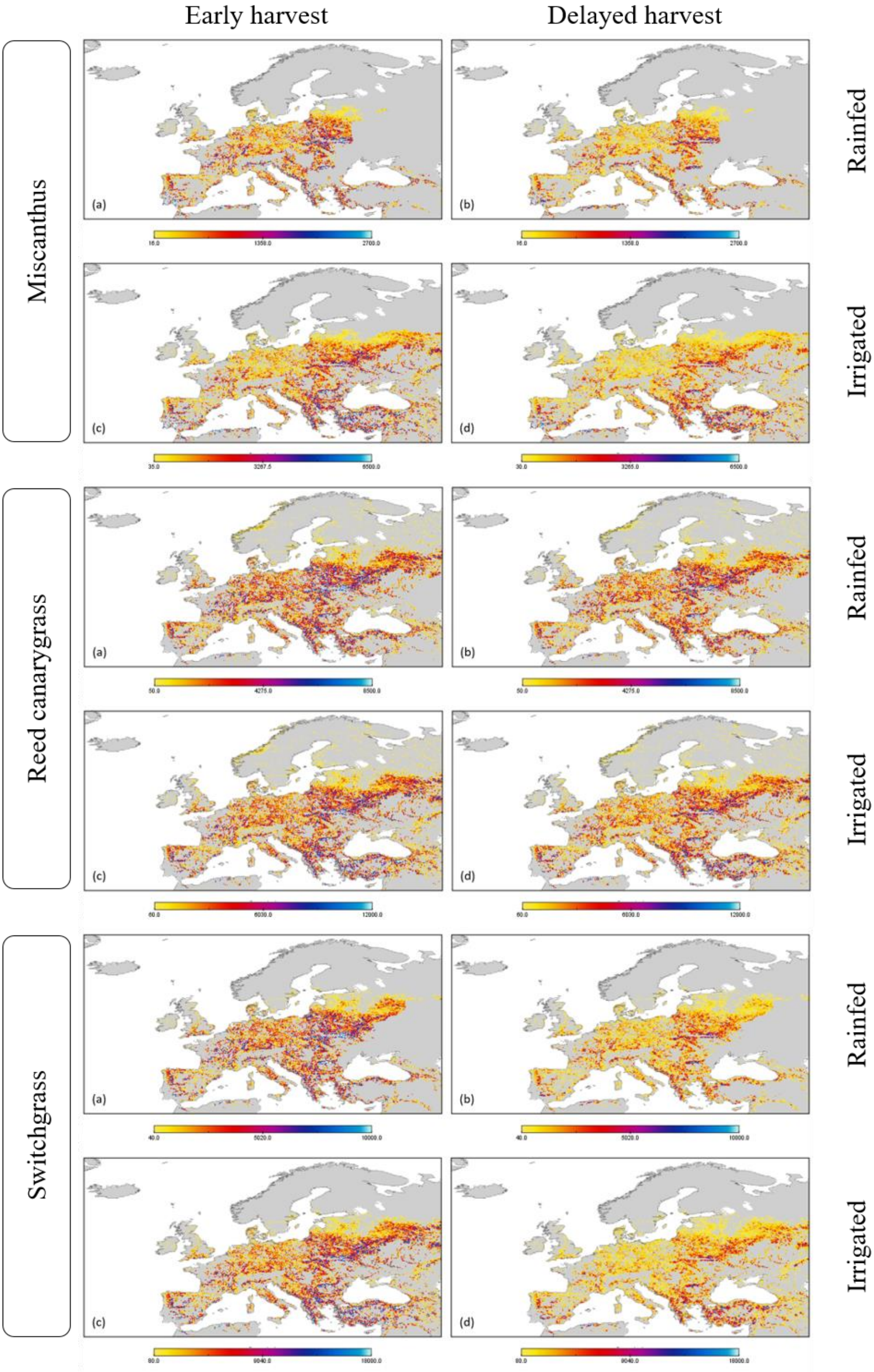
Appendix 33: Total life cycle terrestrial acidification impact from the production of of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe during one year. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\,eq}$/yr) produced. Map scales are based on 5^{th} and 95^{th} percentile and are map-specific.



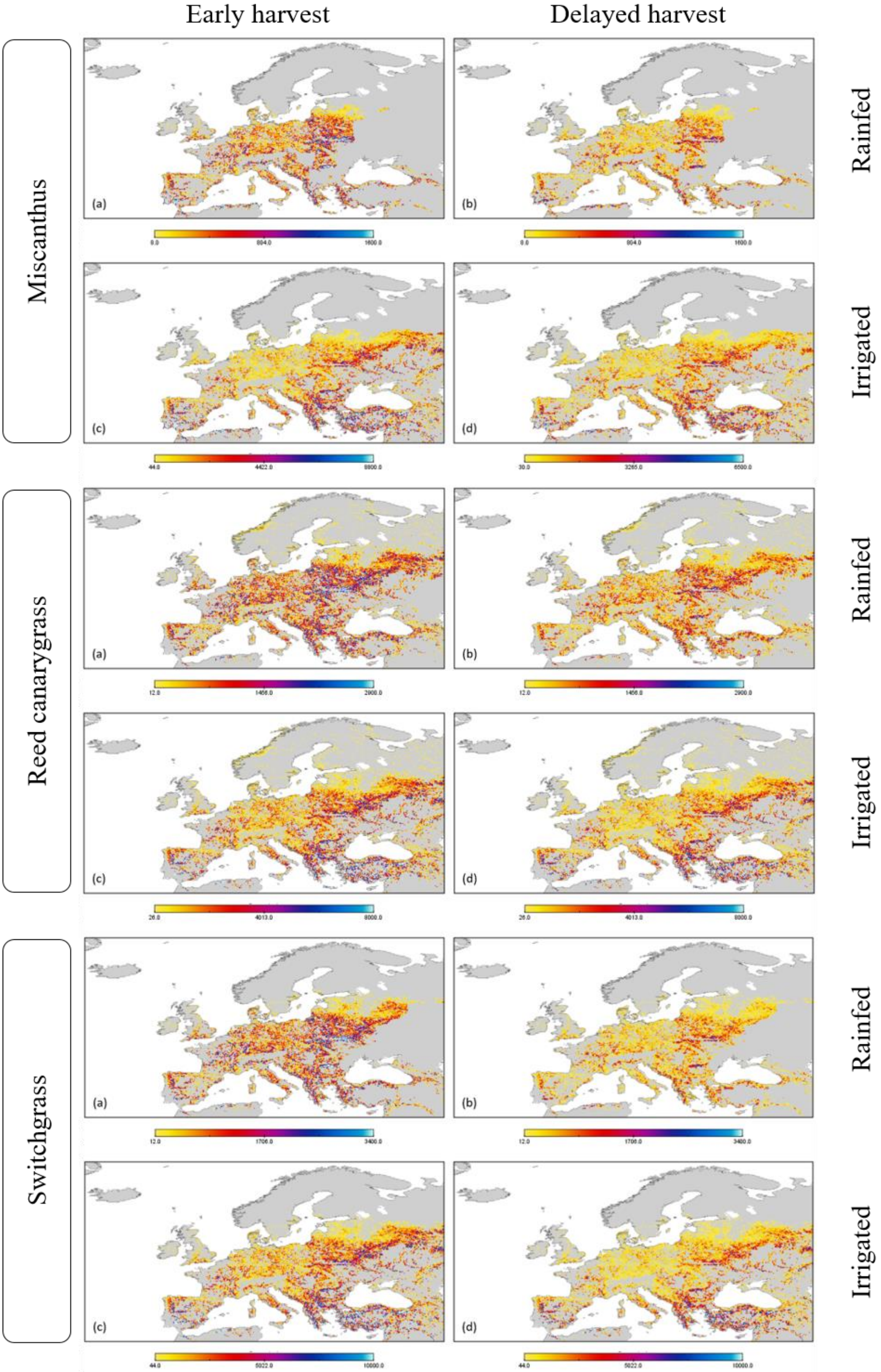
Appendix 34: Total life cycle freshwater eutrophication impact from the production of of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe during one year. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/yr) produced. Map scales are based on 5[th] and 95[th] percentile and are map-specific.



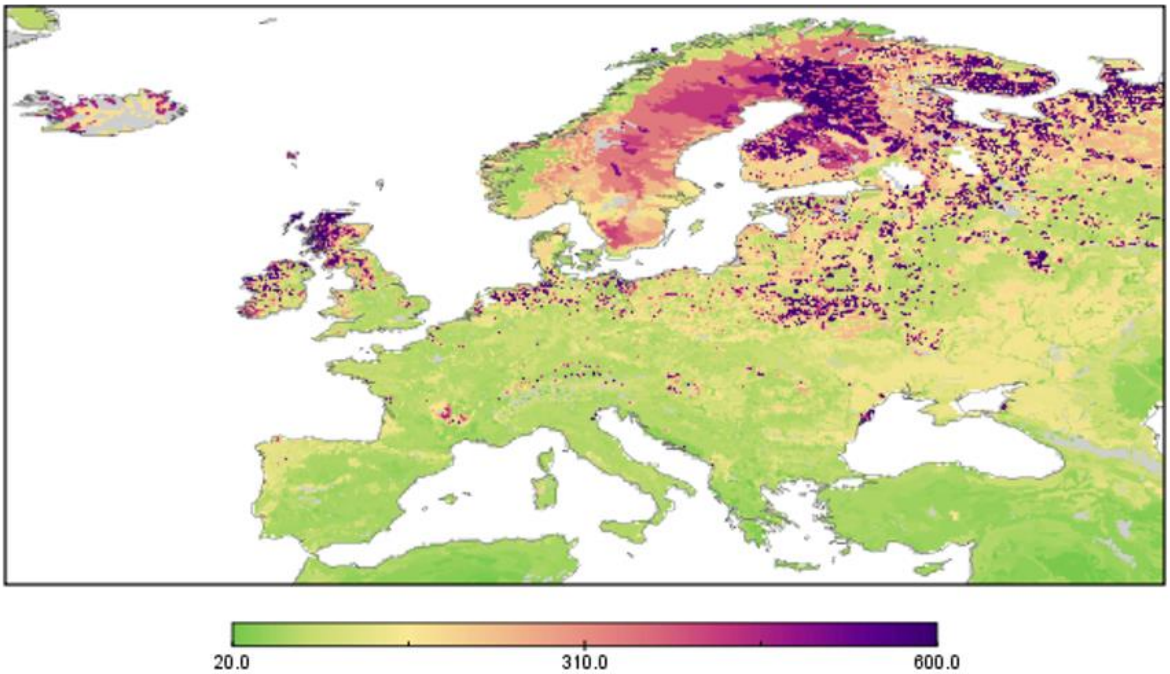
Appendix 35: Total life cycle marine eutrophication impact from the production of of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe during one year. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\ eq}$/yr) produced. Map scales are based on 5th and 95th percentile and are map-specific.



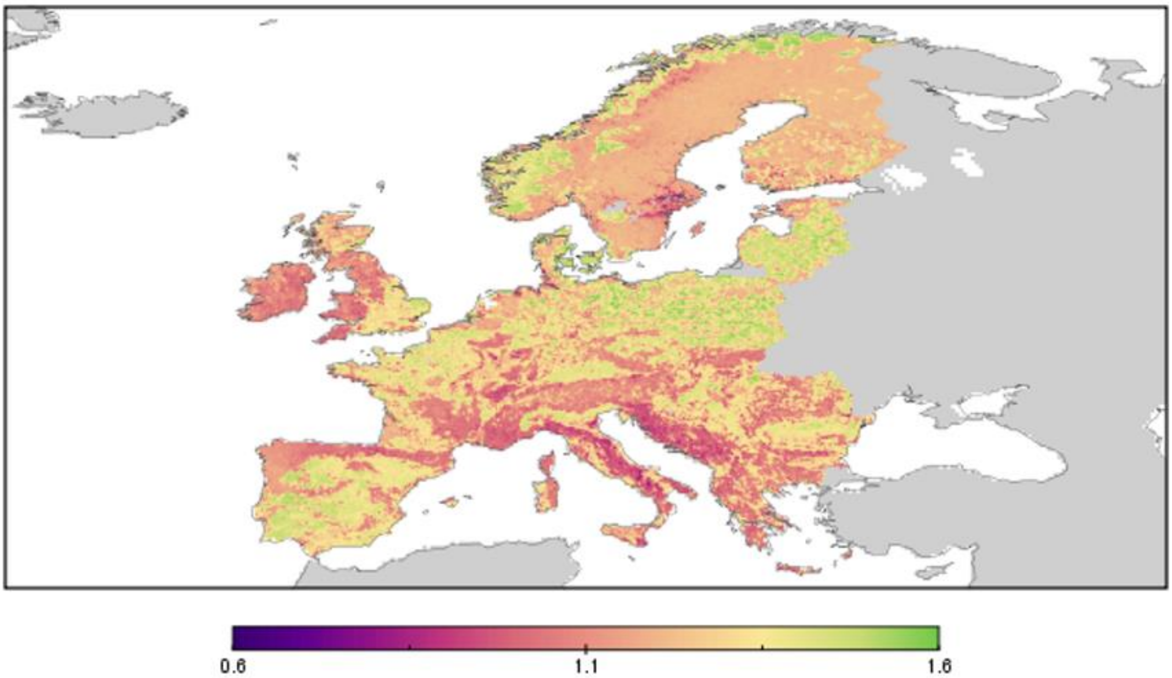
Appendix 36: Total life cycle fossil ressource scarcity impact from the production of of Miscanthus, Reed canarygrass and Switchgrass biomass in Europe during one year. The four scenarios considered for each plants are: (a) rainfed, early harvest ; (b) rainfed, late harvest ; (c) irrigated, early harvest ; (d) irrigated, late harvest. Impact displayed in (kg $CO_{2\,eq}$/yr) produced. Map scales are based on 5th and 95th percentile and are map-specific.



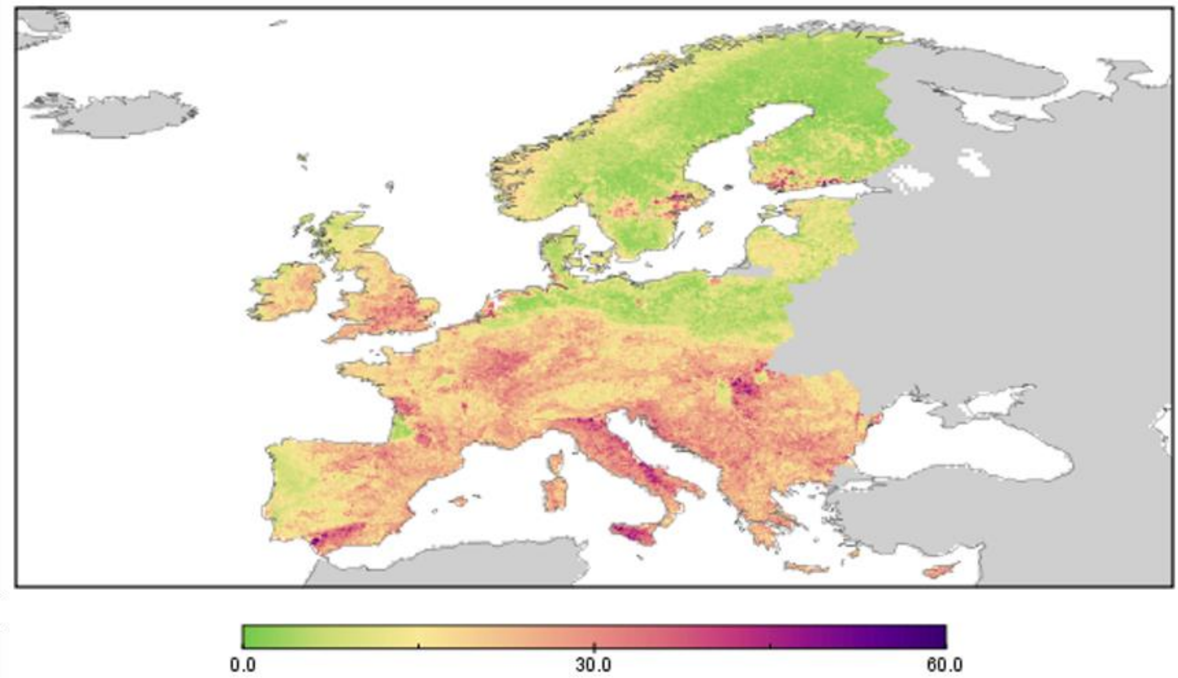
Appendix 37: Initial soil organic carbon stock to a depth of 100cm. (tC/ha). Map provided by the European Soil Data Center (ESDAC) (Hiederer and Kochy., 2012)



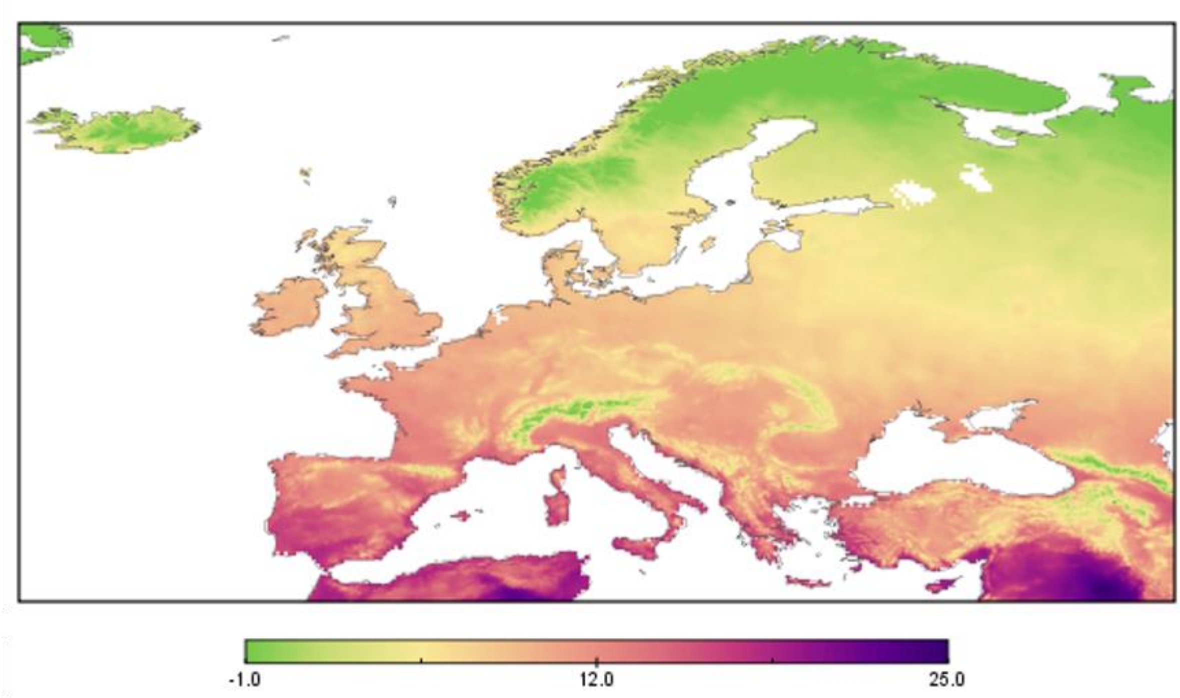
Appendix 38: Soil bulk density. ($t.m^{-3}$). Map provided by the European Soil Data Center (ESDAC) (Ballabio, Panagos & Monatanarella., 2016)



Appendix 39: Soil clay content. (%). Map provided by the European Soil Data Center (ESDAC) (Ballabio, Panagos & Monatanarella., 2016)



Appendix 40: Average European temperature over the period 1970-2000. (˚C) Map from the WorldClim database (Fick & Hijmans., 2017)



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