THE CLIMATE-LAND-ENERGY AND WATER NEXUS: IMPLICATIONS FOR AGRICULTURAL RESEARCH

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1 INTRODUCTION

In a resource-constrained world, uneven distribution and availability of resources can cause stress–and even conflict. With increasing demand, mismanagement can ensue. Thresholds–even those described as 'planetary boundaries' (Rockström et al., 2009a)–are being crossed. Two that result in irreversible damage have been identified: biosphere integrity and biogeochemical flows. Agricultural systems and their transformation in the past 50 years have played a significant role (Campbell et al., 2017; Steffen et al., 2015) in each of them. Agricultural production between 1960 and 2015 has tripled, due to improvements in technology and expansion in the use of natural resources, to satisfy food demands of the population that increased from 3 billion to 7.4 billion in the same period (UNDESA, 2018). Increase in food production per unit of land and labour has led to a significant number of people leaving the 'extreme poverty' box and improved economic status in highly populated countries like India and China. With rising incomes and the global population expected to reach almost 9.77 billion by 2050 (UNDESA, 2018), the demand for food is expected to increase by 50% compared to 2013 levels. This leads to growing incertitude as to whether this demand can be met, without degrading the environment and crossing more planetary boundaries. In addition to future concerns, there exist present-day challenges that warrant global attention. There are severe problems with dietary patterns. High consumption levels in foods rich in fats and sugars (WHO, 2016) have resulted in worldwide obesity nearly tripling since 1975. Nevertheless, global food production in 2012 exceeded demand with some studies indicating that there is indeed sufficient carrying capacity to meet food demand in 2050 (Holt-Giménez et al., 2012); this is undoubtedly a good thing. Indeed, human ingenuity being what it is, it is inevitable that producers (and their governments in turn), will respond to opportunities for increased agricultural production signalled to them through increasingly integrated global markets for food.

Despite the technological and economic breakthroughs that have lifted the global threat of insufficient food for a growing global population, there is still hunger and malnutrition, particularly in countries with civil war and high levels of inequality (FAO, 2017a). For example, food wastage and losses constitute about one-third of all the produced food (HLPE, 2014). Many factors affect this poor infrastructure–storage options, post harvesting and weak institutional frameworks, to name a few. In addition to socioeconomic and technology-based challenges, change in climate also affect the agricultural sector. On the one hand, the agricultural sector along with forestry and land use change (AFOLU) contribute about 24% of the total GHG emission (Smith et al., 2014). On the other hand, climatic change due to increased emission concentrations in the earth's atmosphere is expected to affect every aspect of food production. With the conversion of forests to agricultural land for farming, carbon sequestration potential is reducing; this has been observed in the case of the Brazilian Amazon (Brienen et al., 2015). Development in agricultural systems and climate change also affect the availability and quality of the other resources namely: water, energy and land. That brings us to the definition of the first topic of discussion in this article—the climate, land, energy and water nexus.

1.1 The climate, land, energy and water nexus

The intricate links among energy, water, land and climate (as well as the broader environment) have been well documented for a long time. Loosely grouped into 'sectors', these resources are used to produce goods and services that are then used – by way of 'delivery chains'. Society and the economy use those goods and services, whether they are food from agriculture or air-conditioning from energy. However, Society's 'delivery chains' have traditionally been grouped, and those groups managed in silos. Initially, interactions between many chains were largely inconsequential — their supplies were abundant, and our demand was small. For practical reasons, separate management also allows for delineated responsibility and focused planning. Hence, at all governmental levels, we find authorities for energy, water, agriculture and so on. Each is tasked with their sectoral mandates. Such mandates often do not include any assessments of the impacts of activities in one sector on others (a notable exception is the European Commission's Strategic Environmental Assessments. These assessments are required for certain types of public plans and programs; for example, on land use, transport, waste and water management, energy and agriculture).

Although practical, delineation generally discourages coordination. At best, it misses synergies; at worst, it creates conflict. Sectoral interdependencies are increasing. For a simplified, limited and initial framing, this paper will delineate groups of 'supply chains' as being associated with key resources: Climate, Land, Energy and Water systems. Resources systems, and associated 'supply chains' from these systems are used in different sectorial activities and for management often compartmentalised into a sector.

The linkages between sectors are, however, becoming increasingly important with increasing demands and limited resources. (Broadly speaking) the energy sector, for example, identifies 'energy activities' as those that transform resources into energy carriers, and energy carriers into services. However, many other resources are interwoven into the sector's activities. Take for example land resource – which is essential for cropping and livestock. Productive agricultural land is used, scarred and polluted during fossil fuel extraction. Or, it is covered with growing and extensive solar farms. Similarly, the energy sector competes with water use – another critical element needed for agriculture. It is used in hydro-power generation. Being profitable and similarly strategic - the production of hydro-power affects dam levels and river flows. Both of which impact the agricultural sector's ability to irrigate at the right time. The list of interactions and linkages between sectors – or the so-called 'nexus' between sectors is extensive. (Agricultural linkages are documented in this article).

Agriculture developed from the ability of humans to manipulate and use natural resources, which in turn shaped the way most of humanity lives on the planet. The human behavioural change from hunter-gatherers to farmers transformed how land was used. It led to the emergence of settlements, which in turn triggered a series of social and technological advancements and changes. The context continues to change. There is rapid population growth, growing per-capita consumption increasing calls for national food security and the systems that supply it. These global changes put a strain not only on agricultural systems but also on other sectors. Yet, independently, water resource use and energy use are also increasing. Those, in turn, are linked to agricultural production. These interlinkages can result in strains being compounded – resulting in new management challenges. At the same time, they offer the opportunity for multi-functional solutions.

1.2 The sustainable development goals

With increasing population and rising income levels, the discussion on development in a sustainable manner has never been more relevant (Schumacher, 2010). To carry the discussion on sustainable development forward, the United Nations (UN) and its member states developed the 2030 Agenda for Sustainable Development. It is a comprehensive global plan of action for the people, planet and prosperity. It comprises of 17 Goals (SDGs) and 169 Targets to be achieved by 2030 (UN General Assembly (UNGA), 2015). The 2030 Agenda succeeds the UN's Millennium Development Goals (MDGs), which were a set of 8 goals and 21 targets drafted along the millennium summit in the year 2000. The 17 SDGs and their 169 Targets are highly interconnected and are intended to be more integrated than the MDGs that they replace (Blanc, 2015; Fuso Nerini et al., 2017; Nilsson et al., 2016). Despite their inception and global adoption in 2015, most programs, policies and projects (in different countries) continue to be developed and implemented in their respective SDG-siloes. For instance, some national climate adaptation programs addressing SDG 13 have resulted in violence, conflict, and even death (Nerini, 2018; Sovacool et al., 2017). On the other hand, even, pursuing Sustainable Development Goals at the local level can compromise development in other parts of the world (Engström et al., 2018). These interrelations are due to the self-same interactions between societies 'delivery-chains'.

The SDG framework does not take interlinkages between these 'delivery-chains' and thus the SDGs themselves into consideration. Thus, recent literature has emerged to address this gap by analysing the synergies and trade-offs between the different goals. Fuso Nerini et al. (2017) discuss the implications of the energy-related targets in (SDG7) on the other 16 goals. Wood et al. (2018) discuss the link between ecosystem services (ES) and 41 other targets across 12 SDGs and establish the need for securing them. Singh et al. (2017) discuss the synergies and trade-offs from the point of view of SDG14 (conservation and sustainable use of ocean resources). 12 of the 17 SDGs address sustainable use of resources including water, land, food, energy and minerals, to name a few (Rabi Mohtar, 2016); SDGs 2, 6, 7 and 13 are particularly symptomatic of the nexus between land (food), water, energy, and climate respectively (Ringler et al., 2016).

With an objective to actively contribute to the SDGs and their targets, and to provide a strategic direction to aid its own global vision, CGIAR (formerly known as the Consultative Group for International Agricultural Research) has three broad system level outcomes (SLOs) aiming at reducing poverty, improving food and nutrition security for health and improving natural resources and ecosystem services. Some intermediate development outcomes (IDOs) and sub-IDOs further define the SLOs (CGIAR, 2015). SLO2, on food and nutrition security, is on the same paradigm as the food security focussed indicators of SDG2. This paper explores the synergies and trade-offs between SDG2 & SLO2 and other goals, which are relevant to the climate, land, energy and water nexus, namely: SDG13 on climate action, SDG6 on clean water and Sanitation, and SDG7 on affordable and clean energy.

This article explores agriculture – and its delivery chains linkages or nexus with other sectors by:

- Exploring synergies and trade-offs between SDG2/SLO2 and the other SDGs,
- Cataloguing if, where and how these linkages appear in multi-sector models
- Cataloguing interlinkages across other physical systems
- Identify critical missing interlinkages in integrated assessments (which are designed to analyse the nexus between sectors and provide global development insight)

Moreover, drawing on this, it provides some indicative directions for the future agricultural research agenda, which should help provide policy-relevant nexus analysis insight, process and tools.

The paper is thus organised as follows. In the next section, a mapping activity to identify the synergies and trade-offs between SDG2 & SLO2 and other nexus related goals is carried out. The following section explores the inter-linkages between the agricultural sector and each of the four Nexus resources. Then, we discuss the representation of the agricultural system in integrated assessments (IA) studying the Nexus by classifying them based on their geographic scale. The penultimate section discusses the identified gaps in integrated assessments with a focus on representing agricultural systems and aspires to provide some indicative directions to the global agricultural research agenda. The final section provides some takeaway messages to policymakers on inclusive decision-making and promoting nexus thinking.

2. MAPPING SDG2 & SLO2 TARGETS WITH WATER, ENERGY AND CLIMATE FOCUSSED SDGs

The 17 Sustainable Development Goals (SDGs) of Agenda 2030 and their 169 targets are highly interconnected (Fuso Nerini et al., 2017; Nilsson et al., 2016). Further, the SDGs are also consistent with the CGIAR's System Level Outcomes (SLOs). However, most programs, policies and projects are developed and implemented in their respective SDG category, in isolation. To address this isolated focus, and in concurrence with the nexus between the analysed resources, this section investigates the interlinkages (synergies and trade-offs), specifically between SDG2 & SLO2 targets on zero hunger and improved food and nutrition security respectively, and each of the targets in SDG6 on clean water and sanitation, SDG7 on affordable and clean energy, and SDG13 on climate action. In doing so, key physical linkages between agriculture's delivery chains and its nexus with others are identified. This helps to identify those linkages that may particularly be important for comprehensive development – as detailed by Agenda 2030.

SDG2 on zero hunger has eight targets. They range from ending hunger and malnutrition, sustainable and efficient agricultural production, ensuring seed diversity, supporting changes in the food system with investment to promoting healthy trade environments and markets. SLO2 on improved food and nutrition security has four intermediate development outcomes (IDOs) (with individual sub-IDOs): improving food safety; improving diets for poor and vulnerable people; increased productivity and improved human and animal health through better agricultural practices. While SDG2 and SLO2 have some fundamental differences, they both provide visions for more sustainable, productive and efficient food systems to face this century's nutrition challenges. So, the combination of the two is used for exploring the interlinkages with SDGs 6, 7 and 13 in this section. To understand the interlinkages, this section uses methods developed in Fuso Nerini et al. (2017) and Fuso Nerini (2018), that can be summarised as a structured literature search to look for published evidence on interlinkages between SDG2 & SLO2 and the other SDGs being analysed. The process involved a search for published studies in academic and peer-reviewed grey literature (e.g. UN reports). For this study, a comprehensive review of evidence relevant to each target was not performed. Instead, the authors looked for evidence of some of the most important interlinkages, and a single item of relevant published evidence was deemed sufficient to indicate the presence of a synergy or trade-off between a target and SDG2/SLO2. However, for most targets, several items of published evidence were identified and cited. Results of the analysis are summarised in Figure 1 and presented – together with a description of the delivery-chain interlinkages—in full in the annexe (table –SDG-SLO mapping). Table 1 also reports a summary of the key synergies and trade-offs at the SDG level.

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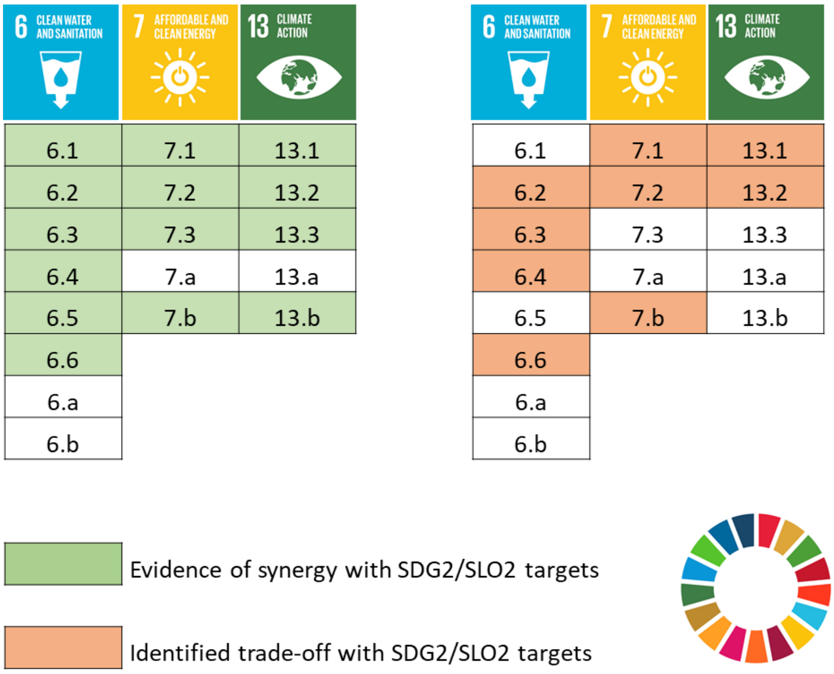

Figure 1. *Interlinkages between SDG2S & SLO2 and the targets of SDG6, 7 and 13. For targets highlighted in green, we identified published evidence of synergies with SDG2 & SLO2 Targets. For targets highlighted in orange, we identified published evidence of trade-offs*

	Key Synergies with SDG2/SLO2	***Key Trade-offs with SDG2/SLO2***
6 CLEAN WATER AND SANITATION	• Water, sanitation and hygiene all needed for addressing malnutrition • Sustainable agriculture to improve water supply and ecosystems	• Ending hunger and malnutrition could affect water availability and quality for other uses
7 AFFORDABLE AND CLEAN ENERGY	• Food systems could be coupled with energy systems (e.g. biogas) • Energy is a vital component for productive food systems	• There could be competition for resources for food production vs renewable energy development (especially true for bioenergy)
13 CLIMATE ACTION	• Climate action can improve agricultural productivity and adaptive capacity of the food system • Sustainable and efficient food systems can better adapt to climate change	• Smallholders could be left behind in climate action • Land use for climate mitigation could affect land availability for food production

Table 1. *Key identified synergies and trade-offs at the SDG level (below description at target level)*

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2.1 Interlinkages with SDG6 on clean water and sanitation

Clean water and sanitation (SDG6) targets are highly intertwined with goals set to achieve zero hunger (SDG2) and improved food and nutrition security (SLO2). We identified published evidence of synergies between six targets of SDG6 and SDG2 & SLO2.

For instance, access to drinking water, adequate and equitable sanitation and hygiene (SDG Targets 6.1-6.2) are all necessary conditions to address malnutrition (SDG Targets 2.1-2.2 and IDO5.3). Further, how water is used in agriculture will affect the achievement of SDG2, SDG6 and SLO2. Sustainable agriculture (SDG 2.4, IDO7) enables the improvement of water quality by reducing pollution (SDG 6.3). Water efficiency (SDG 6.4) and management (6.5) can increase agricultural productivity (SDG 2.3, IDO4), and improve the sustainability of food production systems (SDG 2.3). Finally, sustainable agriculture (SDG 2.4, IDO7), improving soil and land quality support the protection and restoration of water-related ecosystems (SDG 6.6). However, there are also essential trade-offs between SDG6 and SDG2 & SLO2 which need to be taken into account when acting on any of the goals mentioned above. Ending hunger and malnutrition (SDG 2.1-2-2) and improving food safety (IDO6) can have impacts on water availability and quality (Counter to SDG 6.1-6.3) when interventions on the food system are not planned properly. Expanding agricultural systems to ensure food security could result in impacts on water ecosystems - by increasing agriculture-related pollution, and by competing for resources, especially land (counter to SDG 6.6).

2.2 Interlinkages with SDG7 on affordable and clean energy

Five out of six targets of SDG7 have synergies with SDG2 & SLO2. For instance, food systems can be coupled with electricity and biogas production (SDG 7.1-7.2). Further, there is evidence that energy is a vital component of food systems (e.g. in irrigation, food processing and all along the value chain until it is consumed) and will be needed to improve food productivity (SDG 2.2, IDO5). Increasing the share of renewable energy (SDG 7.2) could support improving food safety (IDO 6) by decreasing emissions from the energy sector that could harm the safety of food systems (through local emission of pollutants and climatic change). Achieving SDG 7.2 on renewable energy could also increase the sustainability of food systems (SDG 2.4).

We also find evidence of trade-offs between SDG2/SLO2 and SDG 7.1-7.2, 7.b. Key trade-offs relate to the competition of food vs renewable energy (especially bioenergy) for land and other inputs, and the competition between energy and food infrastructures (counter to SDG 7.1-7.2 and 7.b).

2.3 Interlinkages with SDG13 on climate action

Food security and climate action are profoundly intertwined. Agriculture and food production systems represent 24% of global CO2 emissions (including forestry and land use), meaning that climate action will need to take into account how food systems develop in the future.

In the review of the evidence linking SDG13 to SDG2 & SLO2, we found that four out of five targets of SDG13 have synergies with SDG2 & SLO2. There is evidence that action on climate change can improve agricultural productivity and adaptive capacity in the agricultural sector, thereby increasing food security and access (SDG 2.1-2.2, ILO 5-6). There is also evidence that action on the Paris Agreement can mitigate climate change impacts on food production and help with malnutrition. Further, reducing the friction in the agricultural trade (SDG 2.a.) can lead to better food trade during climatic stress and improve adaptive capacity (SDG 13.1-13.2). Increasing investments and capacity in food systems, could enhance the understanding of impacts and adaptations to climate change (SDG 13.3) and have synergies with capacity for climate change adaptation and mitigations (SDG 13.b). Finally, increasing investment in the areas defined by SDG 2.a will enhance adaptive capacity and resilience to climate change (13.1).

Trade-offs between SDG13 and SDG2 & SLO2 relate to the need to plan climate action in a matter that does not impact food systems negatively, and vice-versa, such as by emphasising large farms in climate adaptation (counter to SDG 2.3).

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Further, land use for climate change mitigation (e.g. biofuels) could be in tension with SDG 2.4 if those affect agricultural productivity and sustainability.

The SDGs and the Nexus

The SDGs and SLOs provide a vision of what humanity should achieve on some of the most critical development challenges. While SDGs and SLOs focus on goals and targets to be achieved, this article will focus on, how agriculture is vital to the climate, land (food), energy and water systems. Nevertheless, as the SDG and SLO goals and outcomes affect how the nexus resource systems develop, understanding the interlinkages among goals presented in this section is crucial to understand how the interlinkages among systems will develop in the future.

3. THE NEXUS BETWEEN AGRICULTURAL SECTOR IN THE CLIMATE-LAND-ENERGY-WATER NEXUS; INSIGHTS FROM INTEGRATED ASSESSMENTS

Understanding the role of agriculture and its nexus with other sectors is essential to manage the use of resources without compromising natural systems irreversibly and thus, inhibiting humanity's existence. Some, critical interactions and nexus between the nexus systems are illustrated in Figure 2.

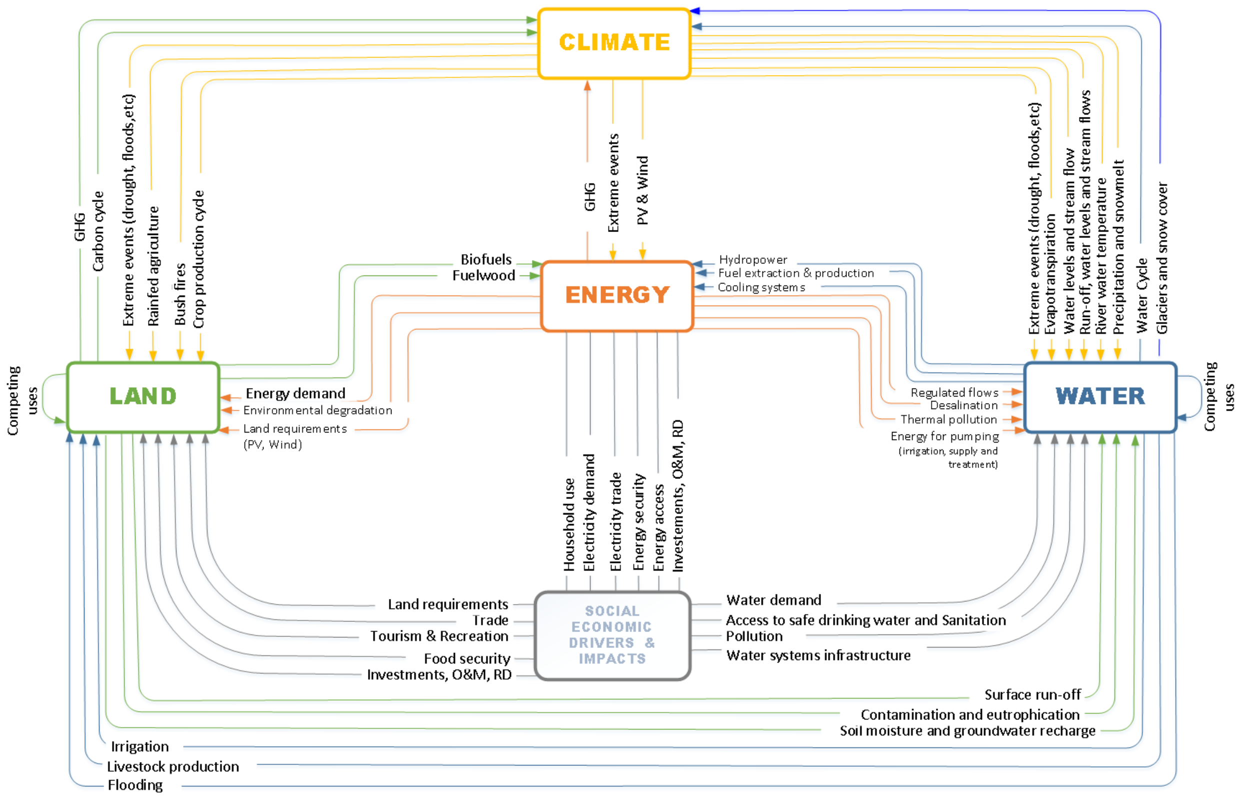

***Figure 2.** The climate, land, energy and water nexus diagram*

Implications of the nexus between the agricultural sector and other nexus systems will be explored in this section; they are described in four sub-classifications, one each for the interactions of the agricultural sector with water, land use, energy and climate systems. The excel workbook, in the annexe, synthesises all identified system wise interactions (as well as a list of models which include that particular link in their framework) and detailed effects and propagations for each of the subcategories. Selected studies and models are reviewed to compile this list. They were chosen based on an attempt to find models and studies where some of the interactions had been documented and addressed. Interactions are not limited to only these models and studies. Furthermore, one model covers more than one impact; thus, model references often repeat.

3.1 Agriculture and Water Resources

Agriculture accounts for around 70% of the total freshwater withdrawals globally; further, area for irrigation has more than doubled, livestock more than tripled and aquaculture more than twentyfold during the last 50 years (WWAP, 2017). This section provides an overview of selected critical interactions between agriculture and water resources.

3.1.1 Agriculture to Water resources

This section presents the impacts or effects that agricultural activities have on water resources.

3.1.1.1 Water quality degradation

Pollution originating from agricultural practices is classified as either non-point (e.g. agricultural run-off) or point source (e.g. discharge from sewers) (FAO, 1996). Agriculture pollutants causing stress on water quality are nutrients (phosphorus, nitrogen, potassium) pesticides (insecticides, herbicides and fungicides), salts, sediments (from erosion and run-off), organic matter (excreta, crops residues), pathogens and other emerging pollutants such as antibiotics, vaccines and heavy metals (Mateo-Sagasta et al., 2017). Among other effects, a load of organic matter entering watercourses consumes the dissolved oxygen, thus causing hypoxia that results in eutrophication. Livestock has associated pollution with its manure.

Additionally, in the past 20 years, antibiotics, vaccines and hormones given to the animals have become an additional cause of water pollution. Aquaculture has associated pollutants such as fungicides, antibiotics and anti-fouling agents; excreta and uneaten food from the fish pose a risk to water quality. On the other hand, there is non-fed aquaculture, such as mussels, which can filter and clean water.

In the integrated modelling framework IMAGE (Integrated Model to Assess the Global Environment), selected interactions between human and natural systems are represented (Stehfest et al., 2014a). In regards to modelling inputs, IMAGE (Stehfest et al., 2014a) provides for nutrient soil budgets (nitrogen and phosphorus) for both natural and anthropogenic activities related to non-point sources. Nutrient fate is further investigated regarding their impact on river systems causing potentially hypoxia and algal bloom. The Soil and Water Assessment Tool (SWAT), developed by USDA Agricultural Research Service, provides an evaluation of land management practices and land use on water, nutrient and bacteria yields (Schilling et al., 2008). Thodsen et al. (2017) study the impacts of nutrient load in six basins in the Baltic Sea region, mainly deriving from diffuse agricultural sources, using SWAT. Four scenarios with fertiliser and manure application are assessed regarding NO_3 and minimum P (minP) load. The study found that the load of NO_3 and minP differed between the basins despite the same increase or decrease in the application of chemical fertilisers and manure. For instance, in Poland, the chemical fertilisers could cause as much as 13% increase or decrease in NO_3 load, whereas the same number for Sweden would be merely 0.06%. A similar trend is displayed for manure application, but with less variance between the countries. These results thus stress and imply that nutrient load is a function of the fertiliser or manure application; however, the nutrient fate is a complex study. Load of nutrients are dependent on the characteristics of the current land area, and not only on the land cover. Despite indicating negative or positive trends, nutrient load from agricultural field ought to be studied on a case-specific basis, and not merely generically.

BASIN (Better Assessment Science Integrating Point and Nonpoint Sources), an assessment tool for watershed-based and water-quality-based studies, allows the study of several water quality parameters such as nitrogen (N), phosphorus (P) and Fecal coliform (FC) and is used on the Little Miami River basin to study nutrient run-off from agriculture and other land-uses (Tong and Chen, 2002). Agricultural land was shown to be the most significant contributor to nitrogen concentration in the run-off; similarly, P leaching from agriculture is the dominant one from urban, forest and barren land. The N load is significantly higher than P. However, run-off from agriculture–especially after a rainstorm–has much larger concentrations of P than N.

The latter implies that in agricultural conservation measures, N should not remain the sole focus, but also incorporate P. Lastly, FC is primarily concentrated on agricultural land in comparison to the other land-uses; they have tendencies of increasing in winter and spring but decreasing in summer and fall. However, the study points out the critical role of

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weather; more or less rainfall will affect the washing of pollutants and thus its spread. Therefore, water quality degradation from agriculture is not only a function of its application but also the weather occurrence.

3.1.1.2 Agricultural activities implicating water quantity

The previous paragraph introduced the quality aspects of agricultural impact on water resources; however, there are also quantity aspects which refer to the agricultural water demand. In this section, we make a distinction between overall water quantity, blue water requirements and green water requirements.

3.1.1.2.1 Agricultural water demand

Water in agriculture is used for: irrigation of crops, water for livestock and for habitation in aquaculture. Particularly for cropping, water productivity, which refers to crop yield per cubic meter of water consumed, is an important parameter when discussing agricultural water requirements. In addition to the aforementioned, water use efficiency, which is water losses (or wastage) when applying it to agricultural fields, is an important measurement when trying to minimise water losses and optimise water usage (WWAP, 2015). Regarding crop water use, depending on the crop type, growth stage and climate, the demand will differ (FAO, 1992a).

The hydrological module in IMAGE (presented in section 3.1.1.1 Water quality degradation) (Stehfest et al., 2014a) is linked with natural vegetation and crop growth in LPJmL (Lund-Potsdam-Jena managed Land) and includes reservoirs for irrigation, as well as hydropower. Within the hydrological model, the water availability and demand from agriculture may be calculated and can also indicate potential water stress as a consequence of high water withdrawal due to, for instance, intensified irrigation. Water use modelling in crop production is also undertaken in The Common Agricultural Policy Regional Impact (CAPRI) model (Blanco et al., 2015), which was recently upgraded to include water use for irrigated and rain-fed crops, and water need for livestock activities under climate change and water variability. The main crop-water variables linking water and agriculture are irrigation water and crop yield. To investigate this new extension of CAPRI, two scenarios of water pricing in the EU are developed. The first scenario investigates a five €cents/m^3 pricing of irrigation water in all EU regions; the second scenario adds to the first scenario an irrigation efficiency improvement of 0.1% for water application and transport efficiency. Results indicate that with an additional water price, total EU irrigated area and irrigated water use would decrease by 24%. However, when also adopting the irrigation efficiency, the decreasing irrigated area amounted to 23%, whereas the water use will decrease by almost 27% instead. This implies that for crops that are highly dependent on irrigation (and are water-intensive), water pricing may thus drive down the production as water becomes too expensive to keep up the same rate of production. The latter could be true for countries in which water supply is inadequate or where small-scale farming is dominating and economical means of irrigation low.

Furthermore, SWAT has been combined with the Water Evaluation And Planning System (WEAP), developed by the Stockholm Environment Institute's US Center (SEI-US) (Psomas et al., 2016) to study seasonal unmet water demand in a small rural catchment in the upper Pinios river basin, Greece. WEAP models the water balance and is to a larger extent focused on urban, tourism and industry sector. Whereas–SWAT models–in addition to the baseline, analyze two irrigation efficiency scenarios: deficit irrigation and upgrade of irrigation network. The two scenarios target a water saving potential of 30% and 25% respectively. However, neither of the two scenarios fulfil their target; the first one can save almost 23% (compared to 30% target) and the second one merely 7% (compared to 25% target). These results may indicate that a single effort of irrigation efficiency measures may not be enough, especially not for high water saving targets. Instead, a combination of several measures can be argued to be required, which target different steps in the irrigation scheme. Another dimension between agriculture and water are their value as common resources in the world trading market. In a globalized market, goods and services are transferred between countries, and thus resources are accordingly allocated.

Combining this into a Land-Water Nexus, Chen et al. (2018) study the flows of agricultural land and freshwater in the global supply chain through a multi-regional input-output (MRIO) model. Contrary to previous studies, this study considers freshwater resources as highly interlinked and interdependent in the global supply chain. The study estimates that about 37% of agricultural land and 29% of freshwater withdrawals are embodied in interregional trade. Both resources are unevenly distributed between trading countries, meaning that flows from resource-rich and less-developed countries to resource-poor and more-developed countries. The latter countries' demand drives the production and trade from other countries; for instance, a source-to-sink budget shows that EU is the largest sink, with the source coming from areas like AU and India. With an ever-intensifying trading market, policies within agriculture that account for interregional trade in the optimization of land and water resources allocation are needed. For instance, in regions with high water stress (e.g. India and Pakistan), it may be more beneficial to maximise crop water productivity, rather than cropland productivity, e.g. through irrigation deficit. In other words, strategies and policies should be made based on both local agricultural production means and possibilities in relations to freshwater availability, as well as the global supply chain and economy.

3.1.1.2.2 Impacts on blue water resources

Within water resources, one can differentiate between green and blue water; the former is important for rain-fed agriculture (explained in the forthcoming section) whereas the latter for irrigated agriculture. The blue water refers to freshwater, and constitutes 70% of irrigation water from river, lakes, groundwater and wetlands (Earthscan, 2007), and is withdrawn from its sources and applied as irrigation on the agricultural field. Similarly, it offers drinking water for livestock and habitat for aquaculture. Increasing irrigation demand and other agricultural water requirements have caused the depletion of non-renewable water resources, i.e. fossil aquifers (Lundqvist and Steen, 1999). Notably, the interaction between surface water (SW) and groundwater (GW) and their respective usage for irrigation have been limited in many modelling efforts (Tian et al., 2015). Groundwater is mostly pumped, whereas surface water is diverted through channels and the interaction between SW and GW is often complicated by the agricultural activities that use both. The two could alter flow regimes both at the surface and groundwater level, particularly in arid and semi-arid regions.

Additionally, in the study by Tian et al. (2015), the author identifies that the operating system in irrigation, such as weirs, gates and pumps, are often not accounted for, and if they are, the groundwater flow is not accurately represented. Thus, Tian et al. coupled the Storm Water Management Model (SWMM) with the Ground-Water and SurfaceWater Flow Model (GSFLOW) to fill this gap. The SWMM-GSFLOW model was applied to the Zhangye Basin, northwest China, which has significant irrigation in a semi-arid climate. Four scenarios are analyzed: ±5 and ±10% substitution of SW diversion by GW pumping. Results showed that when more groundwater pumping was occurring, larger GW-SW exchange occurred, and vice versa. The substitution would cause groundwater discharge to decrease, but the recharge to increase; the former could lead to the base flow reducing and affecting the aquatic ecosystem, or reduce groundwater exfiltration to wetlands and affect desert-oasis ecosystems. On the other hand, not all of the freshwater can be directly used in agricultural activities but is in need of desalination to reduce the mineral content (Beltrán, 2006). Haruvy et al. (Haruvy et al., 2008) developed a water-planning model including desalination of groundwater, wastewater and seawater and applied it on a case study in northern Israel with agriculture as one demand site. Adopting different desalination technologies, all on different feeds (e.g. seawater) results, among others, indicate that desalination of brackish water is most cost-effective, whereas seawater is only recommended when it can contribute largely to the water balance; desalination of wastewater indicated that chloride concentrations could be ensured in agricultural water. However, this implies that pre-treatment of other pollutants have been made. In summary, one can conclude that the management of irrigation supply is dependent for understanding the availability and consequences of using the different blue water resources – and by extension – the other sectors that depend on it.

3.1.1.2.3 Impacts on green water resources

Green water refers to soil moisture in the unsaturated zone that comes from precipitation, this mainly evapo-transpires from landscapes but is used in rain-fed agriculture, and is an important source for livestock and fisheries (Earthscan, 2007). This interaction can be interpreted as both an Agriculture to Water interaction, and vice versa. On the one hand, rain-fed agriculture uses green water; on the other hand, the green water also limits agricultural production. However, it is kept under the former in order to keep the logic of blue and green water together. Rain-fed agriculture is greater than irrigated globally, where about 60% of food production comes from the former (Lundqvist and Steen, 1999). Moreover, if one includes green water uses to the 70% water withdrawal that agriculture accounts for, this number would increase to 90% instead. (IIASA, 2012). Many gaps exist on how much of the water requirement comes from blue and green water respectively. However, a study using a GIS-based version of the EPIC model, GEPIC (Liu and Yang, 2010), indicated that in 2000, 84% of the consumed water globally during growing period came from green water;

the same number over the entire year amounted to 87% of green water. The conclusion was thus that the green water also needs effective water management in relation to agricultural (and other) activities, not only blue water. Furthermore, as green water is held in the unsaturated zone, this is dependent on the soil characteristics as well as the impervious/pervious area. Thus, the land-use has a significant impact on the water balance (Lundqvist and Steen, 1999). Land use and land cover (LULC) change, caused by preparation of agricultural land, affects green water resources through the vegetation interception, evapotranspiration (ET), run-off patterns, surface infiltration and soil moisture (Liu et al., 2017).

Further, agriculture today remains the most significant driver of deforestation (FAO, 2016). However, agricultural land is also exposed to floods and droughts; thus, water use efficiency and water infrastructure (dams, water reservoirs, and other sources of supply) are key elements in the discussion (OECD, 2016). A study by Schilling et al. (2008) used SWAT to study the LULC caused by expansion of the biofuel industry and its impacts on the annual water balance. The study was performed on Raccoon River watershed, which is dominated by agricultural land, with corn and soybean compromising 76% of the land. The novelty of this SWAT study lies mainly in the examination of the impact of warm and cold season grasses on watershed hydrology and pollutant leaching. Several scenarios are run, either based on the expansion of corn acreage or land for ethanol biofuel or land for ethanol biofuel using warm/cold season grasses. Overall, the results indicate that increasing corn production would decrease the annual ET and increase the water yield and losses of nutrients and sediments.

Then again, perennialization would increase ET and decrease water yields and loss of nutrients. The cold and warm seasons grasses prove to have a large effect on the nutrient and sediment loss and cool seasons had more nitrate leachate due to higher requirements of fertilisers; however, the losses decrease when the land coverage increased as well. The study thus confirms that water balance and quality is highly dependent on LULC and its future trajectories, and ought to be an important factor when planning for expansions of agricultural land. However, one should not focus only on the expansion of new areas prepared for agricultural production, but also the changes within agrarian fields and cropping systems and its effect on the surrounding environment. The study above works under the objective of increasing biofuel production (see more in cultivating crops for energy), which calls for the necessity of understanding its effect on the land and water resources.

3.1.2 Water to agriculture

This section presents the impacts or effects that water resources have on agricultural activities.

3.1.2.1 Water policies implicating agricultural activities

As in the earlier section, the interactions between agriculture and water are not limited to physical ones; but rather water sector policies, or other measures or actions, may affect agricultural activities or policies. As mentioned (in a previous section), CAPRI (Blanco et al., 2015), assesses the CAP and its policy interventions; similarly, the Water Framework Directive and other water-related policies (such as water-pricing) are explored, and thus the model allows for the justification of water policies in the water sector in combination with agricultural activities. Changes in water demand, altered by policy interventions, may pose a risk and be constrained by water availability; thus requiring a policy-coherence analysis, which is further covered in the MRIO study (Tian et al., 2015).

3.1.2.2 Water availability constraints for irrigation, livestock and aquaculture

Water availabilities vary over space and time, both naturally or because of additional withdrawal. This variability will thus affect the water supply in agriculture and determine its usage of blue or green water; for instance, in arid areas, green water supply is low and thus implies the need for irrigation with blue water and the loop between water requirements and water availability becomes evident. This variability will affect drinking water for livestock and water habitats for aquaculture. Not all of the freshwater withdrawn is consumed. Instead, it is returned through recirculation to the water bodies (Earthscan, 2007).

Furthermore, reuse of wastewater is emerging to reduce water scarcity but requires advanced technology to ensure sufficient quality (WWAP, 2017). Water can be stored for irrigation or livestock in dams or reservoirs, to be used in times of low availability - called multipurpose dams as they serve several purposes, such as hydropower, irrigation, and flood control (OECD, 2017). But, dams and resource causing disruption in natural flow regime in rivers may pose a risk to the aquatic system and thus aquaculture (Marmulla, 2001). Despite the need for irrigation, it has also caused the depletion of aquifers, reduction of river flows and degradation of habitats and further salinisation of 20% of the global irrigated land area; thus affecting water availability (WWAP, 2015).

In general, many models covering the agricultural water requirements (section 0) are highly interwoven with the water availability and thus model the two in combination. For instance, in IMAGE (Stehfest et al., 2014a), water availability for irrigation is constrained by water from surface water bodies and reservoirs or can be assumed unconstrained to account for prevalent (fossil) groundwater (note, groundwater calculations are not included in the model). The CAPRI model (Blanco et al., 2015), being able to model water use in agriculture, claims to be able to reflect water variability, thus indirectly the water arability. Furthermore, water availability is partially determined by the water balance in WEAP in the SWAT-WEAP study by Psomas et al. (Psomas et al., 2016). The freshwater resources in the MRIO model are not only limited to the freshwater usage within the global trade but can also indicate stress and pressure points of the water availability. The SWMM-GSFLOW model by Tian et al. (2015) reports the interaction between SW and GW with a focus on irrigation schemes. It highlights the importance of accounting for water availability in the two water sources integrated, as the change of availability in one may largely affect the other and the overall storage.

Alternative water supply, such as rainwater harvesting and improved water management practices, could alleviate the stress on conventional water sources. Expansion and intensification of irrigation in the Sava River basin are investigated by (De Roo and et. al., 2016) for the transboundary nexus assessment of water - energy – land (food) – climate and ecosystem services (UNECE, 2016). The agricultural analysis, developed using the modelling tool LISFLOOD (Burek et al., 2013) is used to assess possibilities of improving maize yield. It found that the yield improvement is possible with water scarcity implications for other sectors: energy, hydropower and cooling systems; and ecosystems, as it affects low flow levels due to irrigation.

Cropping patterns are investigated in the water-energy-food (WEF) nexus assessment of the Blue Nile transboundary river basin, shared between Sudan and Ethiopia by (Basheer et al., 2018). The quantification analysis used a combination of modelling tools, RiverWare (HEC), HEC-HMS (HEC), and CropWat (FAO, 1992), which enabled the development of a daily resolution hydrological model. Three transboundary cooperation futures are explored in this study related to the construction of the Grand Ethiopian Renaissance Dam, operation and management of reservoirs in the basin and expansion of irrigation: unilateral action, coordination and collaboration.

3.1.2.3 Agricultural policies implicating water resources

Water and agriculture are not merely limited to physical interactions, but also policy interventions are essential features that may affect the management and practice within, and between, the two systems. For instance, agricultural subsidies and trade agreements would affect the water demand and thus be dependent on water supply and availability, implying the necessity of accounting for such policies in the water sector too (WWAP, 2015). CAPRI model (Blanco et al., 2015), presented in earlier sections assess policy impacts of Common Agricultural Policy (CAP) and trade with a focus on EU level. As for the MRIO model (3.1.1.2.1 Agricultural water demand) by Chen et al. (2018), its results imply the necessity of transboundary accounting of resource shortages and thus arguably be important in Policymaking processes and trade-agreements.

3.2 Agriculture and energy

This subsection investigates the interactions between agriculture and energy systems. The section discusses bidirectional impacts between the agriculture and energy sectors.

3.2.1 Agriculture to Energy

3.2.1.1 Agricultural/Food waste and energy loss

Worldwide about 1.3 billion tons of food is lost or wasted every year, throughout the food supply chain from production to final household consumption; this is equivalent to one-third of the globally produced food (Gustavsson et al., 2011). This implies that the embedded energy inputs, used at different stages of the food chain, are wasted as well. The amount of embedded energy loss in food waste is estimated globally to be 36 EJ/year, which represents 38% of the total final energy consumed by the whole food chain (FAO, 2011). (Parallel observations can be made to embodied carbon emissions as well as embodied water). Further, this waste can be used directly for energy production.

The Swedish Institute for Food and Biotechnology (SIK) quantifies the physical mass of food produced for human consumption and of food lost and wastes throughout the food supply chain using available data, results from the literature on global food waste and SIK's assumptions. Two groups of a) Vegetable commodities and products and b) animal commodities and products are analysed with a mass flow model to account for food losses and waste in each step of the commodity's supply chain. FAO's Food Balance Sheets from the year 2007 and results from the literature were used at each stage of the Food Supply Chain to estimate losses and wastage (Gustavsson et al., 2011). Results show that in low-income countries, food and the resulting energy loss is mainly during the early and middle stages of the food supply chain, which refers to agricultural production and postharvest handling and storage stages[1]. Inadequate harvesting techniques, inadequate storage facilities, limited transportation infrastructure and ineffective packaging and market systems are the main reasons for such high food loss in the low GDP countries (FAO, 2011). Consumers in low-income countries waste much less food (and energy) compared to consumers in middle and high-income countries. Food waste in the latter reaches about 222 million tons per year, which is 1/10th of the global food production in 2011. Several reasons contribute to this such as high 'appearing quality standards', supply exceeding demand, premature harvesting and consumer attitudes (Gustavsson et al., 2011).

In another study, (Cuéllar and Webber, 2010) estimated the energy embedded in wasted food annually in the United States (US) by calculating the energy demand for food production from agriculture, transportation, processing, food sales, storage and preparation for the years 2004 and 2007 (see table in the annexe). Combined with food loss factors from literature, they conclude that the energy embedded in wasted food represents 2% of the of the annual energy consumption in the US with the highest share of waste coming from dairies, then vegetables and then meat, poultry and fish.

3.2.1.2 Food waste to energy (methane, biodiesel, ethanol)

Waste to Energy (WTE) technologies are receiving increased attention on a global level (Ganoulis et al., 2017) in part as wastage is large and growing (Gustafsson et al., 2013). WTE plants such as anaerobic digesters use microorganisms to break down organic waste from food or farms and convert them into energy forms such as biogas (Li and Yang, 2016). The anaerobic decomposition of food waste produces methane, which can be captured by a digester and sent to a generator to produce electricity or heat (Ganoulis et al., 2017). Biodiesel is produced from food waste that has a high content of grease and oil, using methods such as microalgae fermentation and direct transesterification by chemical catalysts and enzymes (Li and Yang, 2016). Whereas, ethanol is produced from processing cellulose and starch-rich crops (i.e. potato, rice and sugar cane) using the fermentation process. The autoclave of food waste before fermentation is often required to improve yield and purity of produced ethanol however it is associated with energy and water consumption (Uçkun Kiran et al., 2014). Globally, around 14 % of all energy used comes from renewable sources, and

[1] This study distinguishes five system boundaries in the food supply chain: 1) Agricultural production 2) Postharvest handling and storage 3) Processing 4) Distribution and 5) Consumption.

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73% of this comes from bioenergy (FAO, 2017a). It can be estimated that 1.32 billion m^3 of methane and 647 kilotons of biodiesel can be produced, globally, which can potentially generate 260 PJ and 24.5 PJ of energy annually (Uçkun Kiran et al., 2014). From an economic perspective, converting food waste to bioenergy requires an investment of ~500 USD/kW and an operating cost of ~0.1 USD per kWh–which is cheaper than solar PV and wind. The levelised costs of electricity for an anaerobic landfill and anaerobic digestion biogas plant using food waste is about 40-65 and 40-190 USD/MWh respectively. Whereas, the cost of Solar PV and Wind power are 130 and 204 USD/MWh respectively (Thi et al., 2016).

3.2.1.3 Cultivating crops for energy

The growing interest in cultivating crops for energy production has raised concerns about competition with effective use of the agricultural area, resources and biodiversity. Additionally, such competition on agricultural land between energy and food systems can increase the volatility of agricultural commodity prices (Ganoulis et al., 2017) And increase food prices. Recent studies on global technical bio-energy potentials conclude that the largest share of future bio-energy production will from plants cultivated specifically to provide bio-energy (Haberl et al., 2010). Globally, about 2% of croplands are used to grow fuel crops (IEA, 2010). Similarly, the World Resource Institute (WRI) estimated that in 2010 about 3 % of the world's cropland is used for biofuel. WRI project this to grow to 15% by 2020 (to meet the target of 10% share of biofuel in transport sector in EU for example) and by 2050 this share will be way far than 15% if the International Energy Agency (IEA) projection, of 20 % share of biofuels in the total energy mix, will be realized by 2050 (WRI, 2013). There is a clear gap in the literature in quantifying the global impact of biofuel (including energy crops cultivation) on land availability for food crops. Meeting a modest 10% biofuel goal for world transportation fuel by 2050 is expected to contribute less than 2% of total energy consumption; yet, would require a significant share of global crop production. This estimate is not taking into consideration , the second generation biofuels.

Several studies developed Geographic Information System (GIS)-based models to assess biomass potential of energy crops at different levels. It is worth mentioning that estimation of crop energy potential is usually investigated from a land use perspective, which reflects the interlinked feature of these systems. Fiorese and Guariso (2010) developed a method to maximise energy production from arboreous and herbaceous crops for the region of Emilia-Romagna in Northern Italy. The technique integrates spatially continuous GIS data with spatially discrete date derived from the agricultural census to assess the productivity of energy crops as well as their contribution to the reduction of GHG. Results show that devoting 2% of regional agricultural land (which is currently abandoned marginal land or set-aside) for energy crops, would increase the share of renewable energy in electricity generation in Emilia-Romagna region by 58%. It will also save 7 million Euros/year in terms of avoided emissions.

Similarly, Thomas et al. (2013) developed a national level geospatial assessment to provide a supply and demand relationship to estimate the biomass potential in England. Three categories of end users of feedstock are identified (a. co-firing; b. Industrial and other large CHP sites and c. Residential/district heating CHP sites), along with their location and the potential demand for feedstock (Miscanthus) is calculated. On the supply side, predicted potential yield data from literature is used to estimate the total potential for Miscanthus cultivation in England.

Additionally, Höhn et al. (2014) developed a study to determine different potential biomasses for bio-methane production in southern Finland. This study by not limiting itself to energy crops, takes into consideration a wide range of available biomass such as bio-waste, sludge, livestock manure and agricultural residues. Among others, this study underlines the importance of rural areas in increasing the share of renewables-based electricity generation. The total theoretical bio-methane potential is estimated to be 2.8 TWh, of which 90% comes from agro feedstocks in rural areas. The use of a GIS-based methodology allows for locating 49 biogas plants with capacities varying from 2 to 8 MW depending on the transportation radius to mobilise feedstock.

Moving away from GIS-based assessments, Pacetti et al. (2015) integrate two methodologies: a life cycle assessment (LCA) and a water footprint study (WF) to comprehensively assess the trade-offs between water use and biogas production from energy crops in Italy. Different combinations of crops, locations and treatments were tested through various scenarios aiming to reach the best performance. The analysis focusses on three stages of the life cycle:

agricultural operations, anaerobic digestion process and energy conversion. This applies to both WF and LCA. For the latter, 18 indicators are used with the focus on climate change, agricultural land occupation, freshwater eutrophication, terrestrial eco-toxicity and water depletion indicators which are more interesting for the scope of the study. Results show that from the WF angle, the cultivation phase has the most impact on water resource use along the entire life cycle. Therefore, in water-scarce regions, the production of biogas from energy crops is often not sustainable. Furthermore, biogas production from energy crops has some beneficial environmental performance (negative LCA impact values) due to avoided conventional fossil energy resource use. This is true for all LCA indicators except for water depletion, freshwater eco-toxicity and marine eco-toxicity.

3.2.2 Energy for Agriculture

Globally, agriculture is the primary earning activity for about 2.5 billion people of which 45% live in developing countries (FAO, 2017a). The sun provides the required energy for the biochemical process of photosynthesis to produce food (Heichel, 1976). In addition to sun's energy, modern agricultural systems also require access to affordable and reliable energy services at different stages of the value chain from production, post-harvest processing and storage to marketing as illustrated[2] in Figure 3. In this section, this interlinkage is further explored.

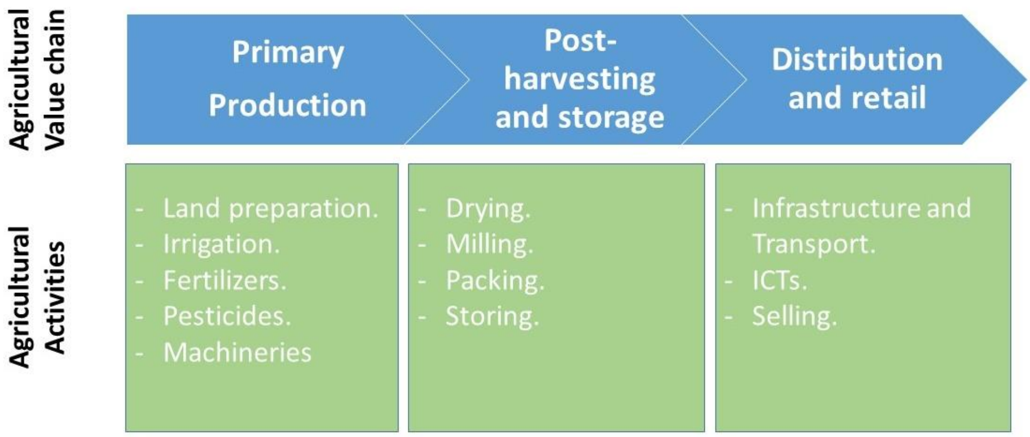

Figure 3. *Overview of the agricultural value chain and main activities considered in this section*

3.2.2.1 Energy for primary production

Primary agricultural production activities were powered by either human labour, draught animals or engine-driven machinery (Utz, 2011). Access to energy in modern agriculture facilitated the shift to mechanization and higher crop yields per unit area, in different parts of the world especially in developed countries (Bardi et al., 2013). However, agricultural production activities in developing countries are still largely dependent on human and animal energy. For example, in Sub-Sahara Africa (SSA) human potential accounts for 65% of the energy needed for land preparation and subsequent weeding (Utz, 2011).

On a global scale, in 2014, the total final energy consumption in farms is 6 EJ/year, of which 1 EJ/year is supplied by renewable sources. This demand is expected to grow steadily to reach 9 EJ/year by 2035. In the OECD countries, this energy is used for water pumping, livestock housing, cultivation, harvesting, heating protected crops in greenhouses, crop drying and storage (Bundschuh and Chen, 2014).

[2] The energy implications of livestock and fish production have not been explored in this section.

The use of fossil fuel powered tractors, harvesters and machinery for primary production activities have reduced human labour inputs and increased the dependency on fossil fuels which were consumed at a rate of 20.4 GJ/ha in high-GDP countries and 11.1 GJ/ha in low-GDP countries (Bundschuh and Chen, 2014). Activities such as ploughing, soil preparation, pulling inputs and threshing require lower skills but greater energy input and mostly powered by draught animals or diesel/gasoline powered tractors (Utz, 2011). In 2005, about 5 EJ of diesel was consumed to fuel 27 million tractors in the world, of which about one-third were operating in low GDP countries, to help with field operation, land development and transport (FAO, 2011).

Irrigation is a major determinant of land productivity; it can double the productivity of land when compared to rain-fed land (Practical Action, 2012). Globally, over 324 million hectares are equipped for irrigation in 2012, of which 275 million ha (85%) are irrigated (FAO, 2014). Energy demand for irrigation is about 0.225 EJ/year, to power pumps, and requires an additional 0.05 EJ/year to manufacture and deliver irrigation equipment (FAO, 2011). Although irrigated agriculture represents only 20% of the total cultivated land, it accounts for 40 % of the total food produced in the world (FAO, 2014). Energy is required to pump water from surface-water (SW) sources as ponds, streams, or canals; or from underground sources like deep aquifers using open wells or boreholes. Distance from the water source to the field, the volume of water to be pumped, irrigation technology, pump technology and the energy source, are key factors to estimate the energy demand for irrigation (Utz, 2011). Traditional irrigation methods, such as manual and surface irrigation, consume low energy compared to more advanced irrigation techniques like drip irrigation (medium energy) and sprinkler irrigation (high energy) (USAID, 2009).

Maraseni et al. (2012) develop an integrated assessment framework to explore the trade-offs associated with the adoption of more water efficient but energy-intensive irrigation technologies. The framework is used to assess the effectiveness of different irrigation technologies at the farm level in five case studies in southern inland Queensland. GHG modelling, hydrological modelling, and cost-benefit estimation are the three main components of the framework that provides estimates of water savings, GHG implications and trade-offs between achieving water security and environmental security. For each farm and crop type, the study compares the farm inputs and the amount of energy (and GHG emissions) consumed in the production, packaging, storing, transportation and application of farm inputs before and after using a particular irrigation technology. Results show that water savings up to 4.5 ML/ha are possible and the highest levels of water savings can be achieved using drip irrigation systems. Water savings, increased yield and labour savings were found to be the most critical factors to economic returns. Additionally, the study found that shifting to new irrigation technologies will reduce the use of farm machinery which will accordingly result in savings in energy and GHG emissions. This can reach up to 15 tons of CO2e/ha.

Greenhouses require high-energy inputs for artificial lighting and heating to grow fruits, vegetables and flowers in peri-urban areas. Due to its particular conditions, the crops grown in greenhouses have a high-energy intensity that can be 10 or 20 times that of the same crops grown in an open field under normal conditions. In addition to the direct energy demand for agricultural activities, there are indirect energy inputs**;** It either comes from the embedded energy during the production, transport and distribution of fertilisers, pesticides and machinery, or in the energy needs for improving water quality such as brackish water desalination or wastewater treatment and reuse. Typically, the indirect energy consumption is much higher than the direct (on-farm) energy consumption (Pelletier et al., 2011). The energy embedded in the production of inorganic fertiliser was around 7 EJ in the year 2000 (FAO, 2011). The farming sector is the dominant pesticide market and the energy requirement for pesticides has been estimated at 10% of the overall energy input per hectare (World Pesticides, 2010). In China, about 60%–70% of energy inputs to agriculture attributes to indirect sources, of which 75% are accounted for by chemical fertiliser (Pelletier et al., 2011).

3.2.3 Energy for post-harvesting and storage

The second stage of the agricultural chain is the post-harvesting phase, which consists of several activities such as drying, milling, packing, storing, processing, to name a few. The type of activities and the energy requirements depend on the crop type, location, economic level and other aspects.

About 30% of the food produced in developing countries is perishable such as tuber crops, fruits and vegetables (Utz, 2011). Therefore, after harvest, proper sorting, drying, grading and packing is essential to reduce losses before storing crops. Drying can be one of the most on-farm energy-intensive activities, for example about 0.5 – 0.75 GJ/t of heat required to dry wet grain down to suitable moisture content for storage (FAO, 2011). In a sunny climate, the cheapest method of drying is laying products out in the sun to dry. However, since the products are exposed to rain and dust, traditional sun drying often yield low quality. Heat-assisted drying is another alternative, which uses relatively inexpensive electricity to create a warm airflow inside the dryer to speed up the process. Solar drying uses a photovoltaic (PV) to drive a fan and create warm airflow (Utz, 2011).

Since the demand for agricultural products is year-round while the production is seasonal, storage is required before sending products to markets. It is a key post-harvest activity, and it is managed locally at the farm level, and in central hubs. Dry storage is used for grains (maize, sorghum, millet, wheat and rice) while fruits and vegetable require cold storage, especially in tropical and subtropical climates. The latter require higher energy to maintain the temperature in the storage facility to an appropriate level (Utz, 2011).

Crops such as maize, sorghum, rice, teff and millet usually go through a milling process, which transforms grain into flour for food preparation. Human, animal, water, wind or a stationary engine, can power Mills. Hybrid systems are also common in different places and provide cost-effective power supply (Utz, 2011). Table 2 shows a comparison in term of energy and time requirements between manual corn grinding and mechanized corn grinding for milling 100kg of corn (USAID, 2009).

Table 2. *Energy requirement for milling 100kg of corn.*

Power and Time Requirements	Manual Corn Milling	Mechanised Corn Milling (Jatropha oil)
Power required/kg of corn/hour	50 watts	50 watts
Power of one person	50 watts for several hours (healthy adult) 100 watts for 5-8 hours (trained athlete)	
Power of 10 hp motorised mill		5.000 watts
Jatropha oil consumed	none	2 litres

PARIKH and SYED, (1986) estimated the energy consumption in post-harvest food systems[3] covering 70 processed commodities in 90 countries across Africa, Latin America, the Far East and Near East. This study showed that the food system accounts for around 17-20% of the total energy use, of which one fifth to one quarter is spent on, in-farm, primary production activities and rest of the energy goes into the post-harvest-food operations. They also concluded that the share of commercial energy used for food processing (like milling, crushing, and food transport and cooking) ranges between 22% in Africa and 80% in the Near East. In a recent study, (Fuso Nerini et al., 2016) developed an analytical framework for the microstructural analysis of the Mukaba Sisal estate in Tanga region in Tanzania using the Long-range Energy Alternatives Planning System (LEAP). The model evaluated several scenarios in order to compare different interventions in the energy and productive sector of the local activities from 2014 to 2030. The model considers the entire chain consisting of primary production, post-harvesting activities and crop conservation and distribution. The study concludes that the lack of modern energy usage can be a limiting factor and a considerable cost for agricultural productivity and development. Furthermore, the modelling effort shows that combining efficient use of energy and production of energy carriers in the farming sector provides excellent potential for boosting productivity and local energy access.

[3] This study considers food processing, transport, storage and cooking as post-harvest food system.

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3.2.4 Energy for distribution and retail

The distribution of agricultural products at retail markets is the final stage of the agricultural value chain. The timely supply of products, to meet consumer demand requires proper infrastructure and means of transport that allow farmers to reach these markets. The transportation of products is mainly powered by fossil fuel based cars or trucks (Utz, 2011). Other activities such as Information and telecommunication technologies (ICT) to facilitate communication between farmers and traders though cell phones, phone kiosks (Utz, 2011) and other modern technologies need to be made available. Wholesale markets are usually located in large cities and are equipped with a large number of appliances, lights, machines, refrigerators and other electrically driven machinery, which again highlights the need for energy in this stage of the agricultural value chain.

3.3 Agriculture and climate

This sub-section will explore the interactions between climatic systems and the agricultural sector. Two (of the many) critical components of the climate change discussion–precipitation and change in atmospheric temperature–are vital for all living systems and directly affect crop production, livestock and fisheries. On the one hand, crops need sunlight, water, suitable soil and temperature to grow; however, on the other hand, both crop cultivation and livestock (along with land use change and forestry) contribute to about 24% of annual GHG emissions (Smith et al., 2014). This section is divided into two parts: one describing the climatic impact on agriculture and vice versa.

3.3.1 Climate to agriculture

3.3.1.1 Impact of climate on crop yields

Plant growth, crop production and yield are a function of different factors including the biophysical components: soils, water, temperature and sunlight (van Velthuizen et al., 2007). The climatic system may influence the suitability and quality of these. There are a plethora of studies that have documented the impacts of change in temperature on different crop varieties across different spatial regimes. Zhao et al. (2017) present a consolidated analysis, exploring the impact of temperature changes on crop yields in four major crops (Rice, Wheat, Maize and Soybean), which constitute two-thirds of human caloric intake using a multi-method analysis. This assessment takes into consideration modelling outputs involving four different methods: global gridded crop models (Rosenzweig et al., 2014), point-based local scale models (Bassu et al., 2014; Li et al., 2015), statistical regression studies and 54 different field warming experiments. The results indicate an expected average yield decrease of 6.0% for Wheat, 3.2% for rice, 7.4% for maize, and 3.1% for soybean, for an increase in global mean temperature by one degree Celsius (This study does not consider CO_2 fertilisation or genetic enhancement in crops). Despite the average decrease in crop yields, the authors highlight the heterogeneous nature of crop yield variations with an increase in temperature also leading to possible yield improvement in a few cases. The latter emphasises the need for a region-specific approach to improve crop yields under warmer climates.

Using a multi-model integrated assessment ensemble, Keith et al. (2017) explore scenario combinations involving the shared socioeconomic pathways (SSPs 1, 2 and 3) (O'Neill et al., 2014; Vuuren et al., 2014) and representative GHG emission concentration pathways (RCPs). They conclude that the difference in impact on crop yields for SSP1 and SSP2 across the different RCPs is not notably significant whereas SSP3 with high emission scenario (RCP 8.5) results in lower crop yields and higher crop prices (Market evaluations). (Oddly, the effects of CO_2 fertilization have again been ignored). There have also been recent efforts in using the social cost of carbon (SCC) as an indicator to capture the impact of temperature induced yield changes on crops. Moore et al. (2017) combine the usage of AGMIP suit of gridded crop models, an open source CGE model based on the GTAP database and an integrated assessment model (IAM) - FUND- to develop new damage functions to calculate SCC, with crop production as the focus. The inclusion of CO_2 fertilisation effects and on-farm adaptation possibilities, which have been ignored in many earlier assessments result in slightly different insights as compared to the earlier observations; the impact of temperature increase is less severe (results from damage functions in the FUND model) as compared to the AGMIP model ensemble results. Leng and

Huang (2017), in their recent study, describe the impact of considering variable crop spatial distribution patterns, to offset the impact of climate change on crop yields. They conclude that changing the spatial crop distribution patterns could offset the climate-induced yield reduction, in corn, by 6%-12 %; this study was restricted to the United States of America.

Atmospheric CO_2 is an essential factor contributing to the augmentation of photosynthesis rates (Challinor and Wheeler, 2008; Kimball et al., 2002). Sakurai et al. (2014), by conducting a modelling experiment, estimate that the soybean yield in the period 2002-2006 has increased by 5.84% on average, when compared to 1980 levels, as a result of a corresponding increase in atmospheric CO_2 concentrations. This experiment takes into consideration historical soybean harvests in China, Brazil and the USA and statistically correlates it with CO2 concentrations for the same period. However, the effects of CO_2 fertilisation get neutralized under an increased drought frequency, as expected with many future climate projections, as discussed by Jin et al. (2017) in their recent study on C3 crops (soybean) in the USS Midwest using the Agricultural Production Systems sIMulator (APSIM), process-based crop model. (Reich et al., 2018), conclude from their recent assessment that the CO2 effect on C3 and C4 crop productivity are not linear and they show a reversal in the CO_2 response dynamics in the period 1998-2017. Thus the understanding of the fertilisation effects of CO_2 is still not robust enough to validate the impact on crop yields. Heat stresses or extreme high-temperature effects crop yields, and they appear to be under-analysed. Siebert et al. (2014) emphasise the need for considering canopy temperatures in modelling exercises to reduce the uncertainty in estimating the impacts of heat stress.

3.3.1.2 Impact of climate on livestock

Climate change is an essential factor affecting the productivity of livestock (Baumgard et al., 2012). With global demand for animal protein expected to rise, the vulnerability of livestock production to climate change raises the concern about global food security (Havlík et al., 2014a). The direct impact of climate on livestock is multi-fold, affecting: growth, production, milk, reproduction, and metabolic activity and disease occurrences (Sejian et al., 2015); heat stress contributing to almost all the categories. St-Pierre et al. (2003) estimate that non-abatement of heat stress, in livestock industries, could result in total losses of USD 2.4 billion annually in the US. High ambient temperatures result in low feed intake, high body temperature and high water intake, resulting in low feed conversion (Marai et al., 2007). It is a natural and evolutionary adaptation process of reducing body weight to decrease body temperatures in livestock (Phillips et al., 1992). In addition to livestock growth, higher temperature and humidity is also expected to reduce milk production, both in quantity and quality. Dunn et al.(2014) calculate the temperature humidity index (THI)- a measure of heat stress- in the UK to analyse the impact of heat waves on milk production and present a case for possible heat wave-induced reduction in milk yield in the UK, using a regional circulation model (RCM); though the adaptive capability to heat stress is varied across breeds. Havlik et al. (2015) use the GLOBIOM model (Havlík et al., 2011a) along with biophysical crop models to conclude that climate change impacts on crop and grass yields are projected to have an only small effect on global milk and meat production by 2050; though the regional impacts vary. Reproduction is another aspect that is affected by higher THI (Gaughan and Cawdell-Smith, 2015).

Climate is also an important factor in disease propagation in livestock. Baylis and Morse (2012) & Morand (2015) investigate the links between the El Niño Southern Oscillation (ENSO) and the African Horse Sickness (AHS) in southern Africa and the North Atlantic Oscillation (NAO) and Infectious diseases in Europe, over the past 50 years, respectively. They conclude that there is an increasing need for more in-depth understanding of the link between global and regional climates to disease propagation in livestock, as it realises a threat to a major source of dietary protein in the years to come.

In addition to the afore-mentioned direct impacts, the indirect effect of reduced water and pasture/forage availability has broader implications on the livestock sector. Elevated heat stress could result in higher rates of evaporation leading to delayed pasture development. Hence, the animals might have to walk/migrate long distances for food (Scanlan et al., 1994); though the effect of CO_2 fertilisation on pastures could have a positive impact in some regions (Havlik et al., 2015). In parallel to feedstock, change in water availability has far-reaching impacts under climate change (Naqvi et al., 2015). Higher ambient temperatures increase the water consumption in livestock and reduction in surface water availability will result in the animals walking a longer distance in search of water, similar to the case of food; although higher precipitation rates in some regions will likely have positive impacts.

3.3.1.3 Impact on pests and insects

The propagation of insects and pests, under future climates, has been a topic of discussion since the inception of the IPCC (Porter et al., 1991). Owing to their poikilothermic nature, insects and pests naturally depend on the atmospheric temperature to regulate body heat. Hence, with the change in average temperatures, the insect propagation is expected to evolve to areas where their existence is a possibility. There are many stylised models, which explore insect and pest propagation: Genetic algorithm for Rule-set Prediction (GARP), Insect Life Cycle Modelling (ILCYM) software (Sporleder et al., 2013), Plant Pest Forecasting System (NAPPFAST), to name a few. Despite many models analysing pest propagation to change in climates, not many capture the entire impact on the crop production system as described by Tonnang et al. (2017). Most of these models assess location and species-specific pest propagation patterns and are not usually linked to and considered as part of integrated assessments. The latest IPCC assessment report (Isabelle Niang and Oliver C. Ruppel, 2014) suggests, with medium confidence that climate change is a major contributor to phenological changes. Moreover, upward shifts (both elevation and latitude) in species distribution could lead to an environment where pests, previously non-existent, could thrive.

3.3.1.4 Extreme weather events

Extreme weather events such as sudden temperature extremes, floods and droughts, storms and hurricanes and forest fires result in considerable destruction to crops, livestock, and lead to substantial financial losses. During the period 2008-2011, the economic impact of a severe drought in Kenya in the agriculture sector was close to 10.5 USD billion (FAO, 2015). Drought is the major contributor to financial losses in the agriculture sector; about 84% of all the drought-related losses (multi-sectoral) are in the agricultural sector (FAO, 2015). Natural weather extremes are specific to a region, and it affects all the different agricultural sub-sectors. Hurricane Felix resulted in damages of about 552 USD million in 2007 in Nicaragua, affecting the annual sugarcane production in the country, along with its Pacific coast (México, 2008). Globally, ~55% of the damages in crops due to extreme weather events are due to floods (FAO, 2015); the floods in Pakistan (2010) resulted in 40% reduction in rice production, eventually leading to a drop in the GDP (Arshad Ali et al., 2011). In some case, floods provide essential silt and nutrients to the agricultural land; as in the case of Bangladesh, where seasonal floods are critical for the delta's high rice and jute productivity (Banerjee, 2010), although severe inundation could result in reduced oxygen and nitrogen availability for the crops. Lesk et al. (2016) & Elliott et al. (2014) describe two methods to assess the impact of extreme weather events on crop yields using statistical and computational methods that could be coupled with crop models to quantify the effects.

3.3.1.5 Impact on fisheries

The fisheries and aquaculture sector, which contributes to the livelihood of about 10-12% of the global population is affected by the climatic. Increases in CO_2 concentration in the earth atmosphere leads to ocean acidification (Brander et al., 2017) and eventually results in lower fish production (Ishimatsu et al., 2005). Deoxygenation is another phenomenon alarming the fisheries sector; soluble oxygen in ocean waters has reduced by 2% in the last 50 years (Schmidtko et al., 2017). Helm et al. (2011), using the results and data from the World Ocean Circulating Experiment (WOCE), conclude that about 15% of the reduction in soluble oxygen in ocean waters can be attributed to the heating up of the ocean layers due to global warming. Cooley et al. (2015) employ an integrated assessment model to illustrate that the socio-economic implications of a reduction in scallop production, by 2050, under a high emission scenario (RCP 8.5) will be significant for the US fisheries sector. Change in salinity is another climate-induced factor affecting fish population, though the change in salinity is not uniform, and its effect on fisheries not consistent globally. Lindegren et al. (2009) take the example of the Baltic cod to illustrate the link between increasing salinity in the region and the decrease in cod production, by using an integrated food web and bio-economic model.

3.3.2 Agriculture to climate

The agricultural sector alone contributes to about 10-12% of the total anthropogenic greenhouse gas emissions in 2014 (Smith et al., 2014). The food sub-sectors' contribution includes changes that extend from the crop production to the consumption. The GHG emissions from a crop production may vary based on many factors: soil type, level of irrigation and geographical location to name a few. Rice, which is the second most produced staple-cop ("FAOSTAT," 2018), is one of the largest contributors to human-induced methane (CH4) emissions in the world (US EPA, 2016). CH_4 emissions per kg of rice cultivated could double by the end of the century, according to Groenigen et al. (2013). That study uses a statistical tool to conduct a meta-analysis of experimental data to conclude that though higher CO_2 level in the atmosphere is expected to reduce rice yields, the demand for rice will increase the land to be brought under cultivation. This will result in yet higher CH_4 emissions. This study also takes into consideration the positive impact of CO_2 fertilisation on rice yields.

Further, surface-standing-water-depth (SSWD) is an essential factor affecting CH4 emission in rice varieties across the world. Sun et al. (2016) use the case of two specific rice varieties in China to conclude that reduction in irrigation water will help mitigating methane emissions irrespective of climate condition and crop variety, but in varieties that are not drought resistant, a dry climate will contribute to reduction in yield. All crops contribute to methane emission in varying intensities; Carlson et al. (2017) estimate the GHG intensity for 172 crop types by location and suggest that mitigation policies should be targeted in regions where the GHG crop intensities are high to have maximum impact.

In addition to methane, Nitrous Oxide (N_2O) emissions have a global warming potential (GWP) 298 times that of CO_2 over a 100 year period (whereas the potential of CH_4 is 25 times)(Danny Harvey, 1993). Nitrous oxide is released from the soil during the denitrification process when nitrogen in manures and fertilisers (as ammonia or nitrates) are converted into N_2 gas by natural bacteria present in the soil (Anne Bernhard, 2010; Nishizawa et al., 2014). A burst of N_2O production is experienced in areas where the ground freezes during the winter and thaws in spring (Wagner-Riddle and Thurtell, 1998). With global warming, there is a concern related to N_2O emissions from the thawing of permafrost in the tundra regions; especially from peatlands (Treat et al., 2016; Voigt et al., 2017). Peatlands in Europe and Indonesia produce about 32% of the total cropland GHG emissions (CO_{2e}) while only contributing to 1.1% of the kilocalories produced (Carlson et al., 2017).

Livestock is the primary source of GHG emissions in the agricultural sector (Gerber P.J et al., 2013). The two main factors contributing to GHG release are enteric fermentation (mostly in cattle) and feed fertilisation. The earlier responsible for methane and the latter responsible for N_2O emissions. There is also indirect emission resulting out of grazing/pasture land and other intermediate processes like storage and application of manures. Global Livestock Environmental Assessment Model (GLEAM), a modelling framework developed by FAO, was developed to simulate the interactions between livestock production and the environment (Gerber P.J et al., 2013). It has been used both individually and along with other integrated assessment models like GTAP and agro-economic models CAPRI to estimate lifecycle emissions (both direct and indirect) from livestock. A recent study by Meijl et al. (2018) compares the impact of climate change mitigation efforts on the agricultural sector, to 2050, across five agro-economic models. They conclude that mitigation strategy for an RCP2.6 scenario will lead to adverse effects on agricultural production compared to a no-mitigation strategy for RCP6.0 scenario; this is partly because of climatic impacts for the scenarios are pronounced only after 2050, though they can already be observed.

3.4 Agriculture and Land-Use

Agricultural systems influence the way land is used. They result from a combination of processes for the production of goods at different scales, including food crops, meat, raw materials, fibres, and bioenergy crops (Jones et al., 2017). As noted earlier, demand from an agricultural system is much dependent on the population growth, on their dietary habits, and caloric intake and economic development (Smith et al., 2010). National policies or goals can also drive food and crop demands. For example, a goal might be to improve nutrition and food security – this may mean ramping up domestic production. This might require increased land demands. However, land uses compete. The land is a natural system that can be converted into artificial systems like settlements, managed forest, energy farms, housing infrastructure etc. As with many other natural systems, it safeguards the provision of key and essential ecosystem services, and its alteration can lead to environmental degradation, sometimes irreversibly.

Land systems are assumed in this paper to include all activities and processes that are related to land, from ecosystems to artificial infrastructure, and use of land for agriculture. Agricultural (and other) land use affect water, carbon, nitrogen and phosphorus cycles (MEA, 2005; Rockström et al., 2009b). About 37% of the global land area (13 billion ha) was used for agriculture in 2015, 29% of which for crop cultivation ("FAOSTAT," 2018). Of the 4.9 billion ha of rain-fed

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cropland potential, 1.4 billion ha of potential remain (Alexandratos and Bruinsma, 2012). Projections indicate that agricultural land is not expected to expand beyond 5.82 billion hectares by 2050 (MEA, 2005). However, the population is expected to reach 9.77 billion in 2050 (UNDESA, 2018), which will push agricultural demand further.

This sub-section describes the interactions between land use and agriculture. Implications thereof are explained and complemented with available quantification. So too are some secondary 'feedback' and related implications. The tables in the annexe summarise these interactions and modelling tools used in their representation and assessment.

3.4.1 Agriculture to land

This sub-section explores important impacts to land use and land systems that can derive from agricultural activities.

3.4.1.1 Agriculture extensification

Land is required for agriculture production, and different agricultural activities have different land intensities. Even within the same activity, production of a certain agricultural good depends on the methods applied, soil types and other characteristics. Although cropland is still expanding (Alexander et al., 2015), yields' increase has allowed for the decrease in land requirements (Smith et al., 2010). However, slow yield increase registered in the past decades (FAO, 2017b) will likely result in the need to expand cropland in the future. A geospatial model to estimate cropland and pastures land requirement is developed by (Meiyappan et al., 2014), at 0.5° spatial resolution for an annual time step. The model is verified again with historic data for the 20th century. Hasegawa et al. (2017) develop a global land-use allocation model that can be coupled with an economy-wide global model. Namely, the Asian-Pacific Integrated Model/CGE. Expansion of croplands due to yield decrease from the use of less suitable land, as well as the extensive and intensive production of livestock, are considered in the Nexus Land-Use global model developed by (Souty et al., 2012).

3.4.1.2 Agriculture intensification

Several factors influence, independently or in combination, yield increase. Output improvement can be obtained with the implementation of irrigation, use of fertilisers, control of plagues and pest with pesticides, genetic manipulation of seeds, analysis of land suitability, (sustainable) agriculture practices, technological improvement, and process optimisation (FAO, 2017c; Smith et al., 2010). Not all of these are affordable for many farmers. This leads to a global diversity in practice.

Mason-D'Croz et al. (2016) developed a participatory scenario approach for designing of stakeholder-relevant scenarios which were investigated using a multi-model ensemble. This included the use of GLOBIOM (Havlík et al., 2014b, 2011b)(Havlík et al., 2014b) and IMPACT 3 (Robinson, 2015a), OLDFAR (Lord et al., 2016) and LandSHIFT (Schaldach et al., 2011) models. Further intensive agriculture affects the local environment. Jägermeyr et al. (2017) find that if environmental flows were to be respected, half of the land under irrigation could face production losses of 10%.

Intensification of agriculture can lead to land degradation, with overuse of fertilisers, over-cultivation, mechanisation, and forest conversion to cropland. An assessment of land sensitivity to land degradation, applied at an agricultural district scale in Italy, was developed by Zambon et al. (2017). The analysis reports a combination of entropy indexes and the Environmentally Sensitive Area (ESA) index and results show that areas with spatial heterogeneity are more sensitive to degradation. Land degradation induced by agriculture intensification in the Messara Valley in Crete, Greece, was investigated by Karamesouti et al. (2015), using a combination of methods: the PESERA model (Kirkby et al., 2000) for soil erosion due to water run-off; the TERON method, to assess tillage erosion (Govers et al., 1994); and land desertification, using the ESA methodology (Salvati et al., 2013). Although soil erosion decreased from the shift in cropping systems, tillage erosion became an important factor of soil degradation. Integrated land management was pointed out as a solution to improve the status of the land.

At the global level, the GLOBIOM model has been used to assess land occupation and potential for GHG emissions reduction as a result of the intensification of cattle and dairy production (Gerssen-Gondelach et al., 2017). The authors compare two cattle production intensification pathways – same production system and transition between systems. Regarding land occupation, it is the transition to mixed systems that allow for LUC mitigation, particularly in Sub-Saharan, Africa and Latin America. The expansion of agricultural area and crop yield increase, as a function of energy and fertiliser prices, also at global level, was investigated by (Souty et al., 2012) using the Nexus Land-Use tool. Potential and actual crop yields were derived from the Lund – Potsdam – Jena global vegetation model (LPJmL). Agriculture intensification in Europe via fertiliser use between 1990 – 2007 was investigated by (Levers et al., 2016) using the CAPRI model.

3.4.1.3 Agricultural trade and indirect land use change

Trade in agricultural goods raises the question of sustainable crop production. On the one hand, food security, diversification of agricultural products, and competitive food prices can alleviate food challenges. On the other, it can create inequalities in access to food; competition for the use of resources; overexploitation of land and water systems leading to environmental degradation. Side-implications of liberalisation of agricultural trade on land use, and GHG emissions are examined by Verburg et al. (2009) using the coupled modelling system, LEITAP-IMAGE. Results for full liberalisation indicate an increase in 6% of GHG emissions in comparison to 2015 value in the reference scenario, due to the conversion of natural vegetation to agricultural land. The study finds that use of land for agricultural production shifts from North America and Europe, to Latin America. Land use futures for the five Shared Socio-economic Pathways (SSPs) are analysed with five IAMs (AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM and REMIND/MAgPIE). In so doing Shared Socio-economic Pathway (SSP) narratives are translated into quantitative representations in the different models (Popp et al., 2017). It is found that global agricultural land by 2100 could decrease by 0.74 billion ha (in the SSP1 – “sustainability – the green road”) and increase by 1.08 billion ha (for SSP3 – “regional rivalry - a rocky road”) in respect to the 2005 value of 4.90 billion ha. Agricultural trade increases moderately even though markets are connected – in the SSP1 scenario. In the SSP3 scenario, agricultural trade is limited due to the “rivalry” narrative, but demands for agricultural goods are high. Global land use implications of agricultural trade are explored by (Schmitz et al., 2012) using the global land use model MAgPIE, in a spatially explicit analysis of land use. One of the scenarios represents a full liberalisation future, which ends in 2045. It is found that although full liberalisation would reduce food prices, this would be achieved with trade-offs to climate, with increased GHG emissions. Agriculture expansion is expected to trigger the land conversion of the Amazonian rainforest.

3.4.1.4 Food consumption, diets and caloric intake

Cultural norms, affordability and diets are changing – with significant impact. Increased food processing and transportation require the use of a variety of resources and materials, and direct and indirect consumption of water, energy and (and thus GHG emissions). The type of diet also influences the demand for specific food products. This is the case of the dietary shift to increased consumption of fish, meat and dairy products as a function of affordability (Alexander et al., 2015). Scenarios related to food losses and waste; and changing diets from several country-level case studies are compared and analysed by (Kummu et al., 2017) to assess the combined potential of increasing food supply. It is found that there is potential to meet food demand in 2050 considering water and land resources available through the combined implementation of measures. The identification of drivers for the use of agricultural land related to the nexus of diet, population, yield and bioenergy was examined by Alexander et al. (2015) via a historical analysis of FAO data for the period of 1961 to 2011. It is found that land use change over this period is majorly driven by increased production of livestock (65%) and, in the latest decades, by the cultivation of energy crops. In (Souty et al., 2012), plant and animal calories demands drive the Nexus Land-Use model calculations, impacting crop yields and land use allocation for cropland and pastures while minimising farmers’ costs of production. The analysis of the dietary shift to low-meat (beef and pork) diets, and increase intake of plant-based protein, has shown to have potential to decrease pasture land considerably, by 2,700 Mha, and cropland, by 100 Mha (Stehfest et al., 2009). The authors, who used the IMAGE (2.4) model, argue that, apart from the implicit health benefits of low-meat diets. The dietary change could be important for climate mitigation, both by lessening emissions from livestock and by carbon uptake from vegetation growth in the livestock vacated land.

3.4.1.5 Interference with ecosystems and biodiversity loss

Loss of biodiversity and ecosystem disruption can be an outcome of the non-sustainable use of land, including agricultural expansion and intensification. Land use allocation optimization techniques, considering trade-offs with ecosystem services, are reviewed and compared by (Kaim et al., 2018). Kim and Arnhold (2018) develop a methodology to map the potential conflict of land use and ecosystem services in mountainous agricultural watersheds. A spatially explicit agricultural suitability index and the Revised Universal Soil Loss Equation (RUSLE) are used to categorise the agricultural watershed in four levels of land use conflicts. Farm management scenarios, e.g. conversion of conflict areas and the management of fallow land, were then investigated to assess the trade-offs between land preferences (agriculture) and environment (soil erosion). Trade-offs between ecosystem services, biodiversity and agricultural production, are investigated by Verhagen et al. (2018). It focused on the optimal allocation of land to different services in a peri-urban agricultural area in the Netherlands. The Constrained Multi-objective Optimization of Land-Use Allocation (CoMOLA) algorithm (Strauch and Pätzold, 2018) is used and considered: a) the maximisation of fruit yields, habitats of endangered species, and landscape aesthetics; b) the minimisation of losses in dairy farming. Novel land demands, such as biodiversity protection and carbon storage, are investigated with the CLUMondo global land simulation model by (Eitelberg et al., 2016).

3.4.2 Land to Agriculture

This sub-section focuses on land systems and agriculture interactions from the viewpoint of land systems and how their characteristics and use can affect agriculture. Similarly to the previous sub-section, effects should not be interpreted as resulting from exclusive interactions.

3.4.2.1 Agriculture potential (crops and pastures)

Not all land is equally suitable for agriculture as well as not all land available can be used for cropland and pastures. Factors as soil type, topography, access to water and climate define land productivity. However, with human involvement, areas not suitable for agriculture can be made fertile (Micklin, 2016). Further, merely understanding the status quo (and changing nature of land use is difficult). Advances have been made in this regard. Y.Chen et al. (2018) develop a new approach for cropland mapping using MODIS-satellite data to calculate a normalised difference vegetation index. Results reach accuracies of 90% for croplands, 73% for cropping patterns and 86% for crop types.

To understand how best to use crop-land (and determine the optimal space available), several models have been employed. The web-based land suitability framework AgriSuit, developed by Yalew et al. (2016), combines GIS and multi-criteria decision analysis, making use of QGIS and the Google Earth Engine. A suitability map is produced as a result of the analysis and shows the spatial distribution of up to four suitability categories (high suitability to unsuitable) for agriculture. Multi-objective land allocation considering climate-smart interventions are investigated by (Dunnett et al., 2018), using the Climate Smart Agricultural (CSAP) toolkit. The multi-objective optimization framework is spatially explicit and investigates the achievement of agricultural production and environmental targets, for different agrarian growth futures that are linked to climate-smart adaptation strategies. At a global level, most IAMs include some form of cropland allocation modelling. Teixeira et al. (2018) investigate the adaptation of multi-crop rotation practices, e.g. by choosing crops’ genotypes and sowing dates, in response to climate change. The crop growth and development simulation model Agricultural Production Systems sIMUlator (ASIM) is used for the analysis, which considered data from six climate models of RCP8.5. Mapping croplands and cropping patterns could be useful for sustainable use of land and adaptation to climate change.

3.4.2.3 Built-up land

Population growth and urbanisation are likely to create particular pressures to land, as 5.2 billion expected to live in cities by 2030 and 6.7 billion by 2050 (UNDESA, 2018). Seto et al. (2012) forecast the conversion, with high probability, of 120 million ha into urban areas by 2030, with changes more expressive in Asia. The Built-up area directly uses the land for settlements and other infrastructure. It can, in this way, compete with prime agricultural land or exacerbate competition between different land sub-systems, such as ecosystems and forests. The impact on agriculture due to urban expansion has been studied by Bren d’Amour et al. (2017) using a geospatial analysis from overlapping cropland and crop yield datasets, with urbanisation expansion probability datasets. Study findings indicate that urban sprawl could result in the loss of 1.8 – 2.4% of global croplands by 2030, 80% of which in Africa and Asia. In the case study of

Michigan's Lower Peninsula, Smidt et al. (2018) investigate the implication of including soil-based development constraints as an urban planning strategy for soil conservation, attributing value to farmland regarding quality, annual revenue from crops, and population density in metropolitan areas. The analysis, performed using the Land Transformation Model (LTM), included the representation of traditional and soil-conservation strategies in the comparison to different configurations of urban area expansion.

3.4.2.3 Cross-sectoral policies

As agricultural policies can shape the way land is used, similar understanding applies to other sectors that require land. Environmental policies and regulation can safeguard forest cover and protected areas. Climate policies can promote afforestation to counterbalance CO_2 emissions. The development of the forestry sector and exploration of forest products, such as pulp and paper and timber, can also contribute to the increase of forest cover.

Renewable energy policies and energy security can increase biofuels demand (and divert land available from crop-production for food – increasing land requirement). If biofuel production is internationally outsourced, then indirect land and water footprints increase, in the case of the 'consuming country'. In the case of the producing country – other agricultural activities might be locked out. This is indicated by preliminary analysis from Segerstrom et al (forthcoming).

Kraxner et al. (2013) use an integrated modelling approach that combines GLOBIOM, EPIC and G4M, to provide a global perspective of biofuels feedstock supply under environmental and biodiversity constraints. Results indicate that the biofuel demand, in 2050, could be achieved by the intensification of agriculture, optimization of land use, fast-growing and short rotation plantations and would imply the conversion of prime forest to managed forest. A review of modelling approaches and tools used to investigate the nexus of biofuels – LUC – GHG modelling was performed by (Panichelli and Gnansounou, 2015), which included a discussion of modelling limitations. The impact of forest preservation policies, at a global scale, is investigated by (Souty et al., 2012), using the Nexus Land-Use tool.

Other energy policy can similarly compete for land – impacting agriculture. Land is needed for wind farms, solar farms panels (**Figure 4**) and it is scarred by activities such as mining. Biomass is often collected for fuelwood in impoverished regions with growing populations contributes to deforestation and land degradation. For hydropower, water is collected in reservoirs – or run of river power plant – and electricity generated. This requires the use of land and the altering or management of water flows. (IAEA, 2009) In the famous case of the Aswan dam, this reduced the fertility of large swaths of agricultural land along the banks of the Nile.

***Figure 4**. A 250-acre solar farm in Datong, China. Source: (Garfield, 2018) agriculture in integrated assessment frameworks*

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4. REPRESENTATION OF AGRICULTURE IN INTEGRATED ASSESSMENT FRAMEWORKS

With the understanding of the nexus between our planets' finite resources gaining traction, there is an increasing need to discern the causal sequences that connect human actions to their consequences (Chopra, 1964). With countries attempting new policies to monitor and consume resources in a sustainable manner, the synergies and trade-offs between decisions made in one sector and their impact on other inter-linked sectors call for attention. So-called, Integrated Assessments (IA) were designed to improve our understanding of the effect of interlinkages between these interacting systems. Models developed to aid this process are typically called integrated assessment models (IAMs) (Dowlatabadi, 1995). The most famous early IAM (though not known by that name at that time) was World3 of the Limits to Growth study (Meadows et al., 1972). More recently, the RAINS model—developed in the 1990s to analyse rain acidification and the long-term impact of policies in the European context (Alcamo et al., 1990)—was one of the earliest examples of usage of IAMs in public policymaking. Since then, the use of IAMs for assessing global climate change for policy analysis and research management has gained momentum. Demand has increased for analytical support; far-reaching national policies are being developed and regular global negotiations—and intergovernmental assessments—are underway, which utilize integrated assessment models.

Further, as climate change mitigation and adaptation are far-reaching, these tools by necessity need to account for sectoral interlinkages—and thus elements of the nexus. They help us ameliorate the understanding of relationships between the different biogeochemical and socioeconomic components of the earth system (Weyant, 2017). Yet, as we shall see, there is much still to be included.

IAMs for climate change analysis are broadly classified into two types: detailed process (DP) models and benefit-cost (BC) models. The DP models analyse climate change on a detailed regional and sectoral level by representing physical impacts like drops in crop yields, sea level rise and melting of ice caps, to name a few—along with some economic implications. Some examples include IMAGE (Stehfest et al., 2014b), REMIND (Leimbach et al., 2010), WITCH (Bosetti et al., 2007; Emmerling et al., 2016). The BC models, on the other hand, are designed to identify an optimal pathway using few economic metrics, usually aggregated over a single or aggregate regions; some examples include the Dynamic Integrated Climate-Economy-DICE (Nordhaus, 1992), Framework for Uncertainty, Negotiation, and Distribution-FUND (Anthoff and Tol, 2013), and Policy Analysis of the Greenhouse Effect-PAGE model (Hope, 2006). Each of these BC models generate an outlook calculating the social cost of carbon (SCC). The SCC is the incremental damage (in financial terms) caused by one extra ton of carbon emissions, under different development scenarios.

Despite the use of IAMs to improve our understanding of the nexus between water, energy and climate and land systems (Kling et al., 2017), most of them focus on a limited set of interactions. This is typically between two systems and they do not or only partially explore the propagation effects and feedback loops into other linked systems. Some tools explore this nexus on different geographical scales. Some focus on the economy and trade interactions relevant to the nexus. Whereas others do not use models as the 'entry point'. They explore qualitative aspects affecting the nexus though stakeholder engagement workshops for effective discourse. The agricultural sector is a critical link between the human (society) and natural systems, contributing to and withdrawing from crucial resources that represent the biogeochemical cycle. Despite this, its representation in integrated assessments for assessing the nexus has been varied. Ruane et al. (2017) discuss the simplified representation of the agricultural sector in IAMs and propose a more robust framework for better depiction by linking crop model and climate model emulators with IAMs.

In the following sub-sections, we explore the representation of the agricultural sector in:

- Selected Global IAMs for climate change that feed into the IPCC assessment reports.
- Other integrated assessments efforts that focus on the nexus between climate, land (food), water and energy systems.

4.1 Representation of agricultural systems in IAMs to assess climate change

In this subsection, we explore the representation of the agricultural sector in one detailed process (DP) and one cost-benefit (BC) IAM developed for exploring the impacts of climate change.

IMAGE, is a dynamic, detailed process IAM maintained by PBL-Netherlands Environmental Assessment Agency (Stehfest et al., 2014b); it explores the complex interactions between the human and earth (natural environment) systems through direct and indirect relationships and feedback loops with external drivers. The IMAGE model consists of different modules/models, which resemble the components of the **DPSIR** (Drivers, Pressures, State, Impact, Response model of intervention) framework (Smeets and Weterings, 1999) to examine the different human-environment interactions. In IMAGE, the agricultural sector is represented by a set of soft-linked models as described below:

- <u>MAGNET</u>: An agro-economic model based on the established computation general equilibrium model (CGE) GTAP. The objective of MAGNET is to determine regional production levels, related crop yields and livestock efficiencies. It takes into account changes in technology and biophysical conditions (Geert Woltjer and Marijke Kuiper, 2014). It takes input from all the other modules to produce spatially explicit outputs related to crop production, optimal trade dynamics and sectoral demands—to name a few.
- <u>Land-use Allocation Module</u>: a dynamic land use allocation model is used to interact with the crop module and the MAGNET model. A key output from this module is the fraction of available agricultural land by crop type, per grid cell. A dynamic link is established to the land systems change model—CLUmondo (Asselen and Verburg, 2013)—which produces land suitability maps taking into consideration many site-specific constraints including biophysical and socioeconomic indicators.
- <u>Livestock Module</u>: This module explores two types of livestock production systems: Pastoral, mixed and industrial. By utilising critical outputs from the MAGNET model and some external datasets, this module estimates animal stocks, grass and feed crop requirement, depending on the development scenario (Bouwman et al., 2005).
- <u>Crop and Grassland module</u>: A dynamic global vegetation, agriculture and water balance model called Lund-Potsdam-Jena model with managed Land (LPjmL) (Bondeau et al., 2006; Gerten et al., 2004; Sitch et al., 2003) is used to represent the process based interactions and other system dynamics in between vegetation, carbon and agricultural production. The model considers climate based smart agricultural practices, in long-term scenarios, to adapt to a changing climate (Waha et al., 2011).

The Climate Framework for Uncertainty, Negotiation and Distribution (**FUND**) is an integrated assessment model developed to perform cost-benefit (BC) analysis on climate change impacts and analyse the effectiveness of adaptation and mitigation policies (Anthoff and Tol, 2013). Over the past years, the model has been used to estimate the social cost of carbon for the 16 dis-aggregated regions of the world. The FUND model uses the IMAGE database for its basic economic and demographic information to calibrate. The climatic impact on agriculture is represented in three parts: an imperfect foresight component where the farmer is not aware of the climate, a component representing the rate of climate change and a final component representing the carbon dioxide fertilisation effects. The FUND model, being a BC type model, does not have the detailed representation concerning crop varieties but aggregates the climatic impact through damage functions taking into consideration the net climatic benefits in the agricultural sector.

4.2 The agricultural sector in integrated assessments that study the Nexus

In this subsection, we explore the representation of the agricultural sector in integrated assessments focussed on quantifying the nexus between water, energy, land and climate systems. They primarily include quantitative assessments, and a few prominent qualitative nexus studies. We then categorize them based on their spatial resolution into global, trans-boundary river-basin, national and sub-national/regional scale. Tables in the annexe provide an overview of all the assessments that were analysed along with information on the representation of the agricultural sector, selected limitations and availbility of the tools/models used.

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At a **global level,** there have been varied approaches to explore the nexus. Ringler et al. (2016) present an IA involving two modelling frameworks: the global computable general equilibrium (CGE) model GLOBE (Thierfelder and McDonald, 2012) and the international model for policy analysis of agricultural commodities and trade (IMPACT) (Robinson, 2015b). By disaggregating the entire world into 320 different food-processing units (FPU) to study the impact of carbon taxes on water and food prices, they conclude that, a fossil fuel tax would not affect the security of food supply adversely. It could improve global food security if it reduces adverse climate change impacts. In another study, Damerau et al. (2016) estimate the global water demand for food and energy supply by employing a two-part accounting and linear optimization framework. They use information on the water footprint of food production to meet the global food demand by using inputs from water food print (WFP) network (Mekonnen and Hoekstra, 2014). The nexus assessment does not explicitly model the agricultural sector but uses scenario-based thought experiments to represent it. They arrive at the conclusion that water demands could be reduced by taking into consideration dietary changes such as macronutrient shifting. Van Vuuren et al. (2015) discuss the need for an optimum combination of technological improvement and behavioural change for achieving sustainable development—taking the WEF nexus into consideration. Using the IAM, IMAGE, they conclude that the agricultural sector would need about 1% increase in average annual productivity to sustain the demand for food. Taliotis et al. (2016) develop a simplified global model using the open source energy modelling system (OSeMOSYS)(Howells et al., 2011). The model is a linear long-term optimization model with demands for food, water, energy, land and other material resources being the drivers. With a consolidated representation of the agricultural sector, they try to capture the impacts of development policies on the energy system. It notes that with increased low carbon energy production, demand for water in agricultural sector will increase—as biofuel production will need to be supported.

On a **transboundary (TB) scale**, the nexus between resource systems has been approached through qualitative and quantitative techniques. Guillaume et al. (2015b) develop a methodology to improve the understanding of the nexus in transboundary river basins in Central Asia by using a WATERGAP (ALCAMO et al., 2003) model of the region disaggregated into FPUs. Since the consumption of water due to excessive irrigation has resulted in the drying up of certain lakes, this assessment tries to capture the crop production sector and its water demand in good detail. Ethan et al. (2016) use the Indus Basin Model Revised-Multi Year (IBMR-MY), an agro-hydro economic model, specially built to study the Indus River basin and study the energy and water implications on the agricultural sector. The model splits the TB region into different agro-climatic zones (ACZ) and the demand for food and energy are projected for each of them. De Strasser et al. (2016) describe a qualitative stakeholder engagement approach for transboundary nexus dialogues involving representatives from multiple sectors (including agriculture); the framework was developed as part of UNECE's river basin assessment studies. It invokes selected models and quantification as a function of critical challenges identified by stakeholders during a workshop called the 'nexus dialogue'.

From a **national** perspective, most of the reviewed studies tend to be quantitative. Welsch et al. (2014) and Howells et al. (2013) use the climate, land, energy and water strategies (CLEWs) framework for the island nation of Mauritius to analyse the cross-sectoral implications of producing first and second-generation biofuels in the country. They use a combination of different tools, one each for the different systems and soft link them to perform the nexus study. They use the agro-ecological zoning model (AEZ)(Fischer et al., 2002) for crop statistics and implement them in a water balance developed using the water evaluation and planning tool (WEAP)(Yates et al., 2005) to calculate seasonal water demands for crop production (both irrigated and rain fed). The analysis estimates the water and energy requirements of growing sugarcane for bio-fuel production and how the climate and market price fluctuations may play a significant role in affecting this decision. Other engineering based assessments exist, where the agricultural system (primarily food production) is only the driver; Lubega and Farid (2016) present one such example for the case of Egypt where the energy and water implications of an extensive irrigation program is discussed using the systems modelling language (SysML)(Balmelli et al., 2007). This systemic assessment does not have detailed crop representation; it takes the periodic crop water demand for irrigation as an input. Daher and Mohtar (2015) present a tool for assessing the WEF nexus by developing an analysis for Qatar. The online tool allows the users to create scenarios based on science and policy inputs; it estimates a sustainability index for the different resources. Only food production is included as part of the agricultural system. The interactions are defined based on aggregated national data and inputs from parameters collected for a specific country (Qatar), though the approach is replicable.

Several modelling frameworks exist which focus on sub-national level nexus; Karlberg et al. (2015) describe a methodology using tools WEAP and LEAP to assess the nexus in the Lake Tana region of Ethiopia. They identify two main hotspots with respect to increasing instability in the water balances of the region and biomass availability reaching a limit. MuSIASEM (The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) model is used by Giampietro (2013) for analysing the nexus interlinkages in three different sub-national case studies: Mauritius, the Indian state of Punjab and South Africa. The agricultural sector and its links are represented as part of a flow-fund diagram, which is the basis of the model. It also has some unique features to capture unpredictable loops in the system.

The representation of the agricultural sector (food, fuel, fibre and feedstock) across nexus assessments has been varied. Some take into consideration the climatic aspects, whereas some consider climate as an external entity and focus only on the WEF nexus. Moreover, amongst those that explicitly consider climate, only a few take climate uncertainty into consideration. Amongst those that focus on food security, most of them take into consideration the average daily calorie intake. However, the nutritional component is not represented adequately. It is critical to assess SDG2 and SLO2 targets that focus on not just daily calories but also nutritional requirements. The policy relevance of global models and their adaptability to feed into national agendas remains to be explored; especially from an agricultural point of view.

Similarly, despite the availability of country-specific climate-smart agricultural (CSA) profiles and suggestions, there is still a gap in how nexus assessments that focus on agriculture consider adaptation options. Brouwer et al., (2018), in their recent article, discuss the resource nexus and IAMs by comparing six different integrated modelling frameworks to conclude that there exists no one tool that answers all questions, but a mix of tools are used to address few interlinked sectors. Linking models with different spatial and temporal resolutions and behavioural dynamics call for several improvements. A more robust scenario definition routine is needed. The usability and availability of tools can be a barrier. Many tools and frameworks are not fully open sourced, or their reproducibility has been questionable. The latter is a critical issue to be addressed when the SDGs call for effective capacity building in developing countries. A useful step would be to establish an enabling environment that would help support an ecosystem with symbiotic supportive research. Therein some 'lighthouse' efforts to build integrated bi- or multi-sector action plans should be initiated. These might specifically integrate agriculture development with other sectoral development.

5. SELECTED GAPS IN INTEGRATED MODELLING METHODOLOGIES AND RECOMMENDATIONS FOR FUTURE AGRICULTURAL RESEARCH

Research on the climate, land (food), energy and water nexus has increasingly progressed since initial initiatives such as CLEWs (IAEA, 2009), Global Risks Report (World Economic Forum, 2011) and the 2011 Bonn, Nexus conference (Hoff, 2011). The intiatives mentioned above highlight the need for an inclusive and integrated approach to understanding synergies and trade-offs between resource uses. Since then, there has been a deluge of assessments that explore nexus interactions between different systems. Apart from assessing the direct system-to-system interactions, these may have multiple foci and consider feedback loops, propagation of impacts, trade-offs and synergies between the assessed sectors/systems. Further, only a very limited set of assessments attempt to map relationships in a policy relevant manner; such as Nilsson et al. (2016) that go beyond considering simply 'synergies' or 'trade-offs' and describe actions as "indivisible, reinforcing, enabling, consistent, constraining, counteracting or cancelling". Even those that do are not yet able to quantify those interactions explicitly (rather, depending on expert judgement). In this section, we identify some limitations and gaps in the literature of analytical assessments that investigate nexus interactions between agriculture and one or more of the systems of climate-, land-, energy-, water- and societal-systems.

5.1 Agriculture and Energy

Agriculture requires (and provides) energy. It uses energy in various forms throughout the different stages of the process chain, from land preparation and cropping, to finished product and residues. However, the accurate assessment of how much fuel is required (or produced) along the production chain is limited. Below we draw attention to specific knowledge gaps that have been identified between these two systems and/or their sectors

- There is a need for assessment and documentation of energy consumption in complete agricultural cycles (from land preparation to waste production and reuse). Energy consumption over the entire value chain, from the field to finished product, needs to be taken into consideration, which is not done in many assessments. Most studies focus on only the specific activities of the chain, which do not give a comprehensive picture of the total energy consumed.
- Quantification of energy implications in an agricultural product's value chain, beyond the end-user, is lacking. Waste, residues and by-products similarly form important energy (and other) production feedstock, and could play a key role in diversifying the economy, contribute to the optimisation of industrial activities (e.g. more efficient processes, cogeneration), as well as provide alternatives to conventional fuel sources.
- Integration of energy use accounting in agriculture expansion and modernisation plans is missing. Therein over a million people are without electricity on the one hand, while electricity access (an essential part of SDG7) planning is often blind to the role that agro-industry based mini-grid, and grid-generated electricity supply can play.

5.2 Agriculture and water

Agriculture and water are interwoven; as water is one of the basic requirements of life on Earth. The use of water, along with its availability and quality, are important factors for agricultural production. Moreover, as water resources are required by several sectors they become particularly vulnerable resource. Below we highlight specific knowledge gaps identified in the literature review for the particular case of agriculture and water analyses:

- An inventory of water saving solutions across the agriculture value chain is needed. The documentation should include implementation examples, particularly what motivated the deployment of specific solutions. For instance, water harvesting is used for agriculture in Jordan, helping to mitigate the arid climate and variability of water availability (Sixt et al., 2018), but many analyses in arid areas do not consider the same in their assessments. In other instances, constructed wetlands have been used for natural water purification (Jordan et al., 2003).

- Understanding the costs incurred by polluted water on agricultural activity is critical to developing a cost-benefit analysis for remedial or preventative action. There is plenty of quantification on water pollution in agricultural economics, but its usage in IAMs can be improved (Mateo-Sagasta et al., 2017) and made straightforward.
- There is limited consistent analysis of pollutants and their transport in various natural cycles and in agricultural product chains. Nitrogen and Phosphorous are notable examples. While related to pollution (not just water-based) better quantification, representation and response from abiotic (sunlight, nutrients, water) and biotic (insects, pests) factors (Ascough et al., 2018), to agricultural practices, is generally needed.
- There are limited (appropriately granular) Geographic Information System (GIS) data sets easily accessible and open (Ascough et al., 2018) that inform on soil properties, soil water contents and some other soil-related key parameters. The latter are essential to quantify agriculture and water (as well as other) interactions.
- Several run-off water models exist and are in general use. Many of these, when used in nexus assessments, do not account for – or accurately treat - groundwater as a source for irrigation, nor consider future changes to land use in the projection of run-off. Their widespread use can cause and propagate errors in the actual water balance (Stehfest et al., 2014; Tian et al., 2015). The latter is essential for planning.

5.3 Agriculture-climate

Climate affects agriculture and is affected by agriculture. Climate change is associated with changes in ambient CO2 concentrations, precipitation and temperature patterns. Each of which affects the growth of plants, livestock and fish. Further agriculture is responsible for GHG emissions associated with fertilizer application and production, fossil-fuel-derived energy use, and land-use change, among others.

- (Often contentiously raised by climate sceptics) Increasing CO2 concentration can have a fertilising effect on plants. This is yet to be accounted for in most IAM's. A future with accelerated climate change, is likely to be characterised by high GHG levels in the atmosphere; this may affect the swiftness and potential for adaptation.
- In considering the cost of mitigation action and inaction, uncertainty analysis is essential. Climate uncertainty within General Circulation Models (GCMs) – and their downscaling - is often not assessed in terms that readily relate to on the ground climate action – or climate proofing. An advance in scientific knowledge at this level is necessary to better inform agricultural planning. Fledgeling efforts such as a recent assessment of the climate vulnerability of African agricultural and energy infrastructure to climate change is one such example (Cervigni et al., 2015). Similar assessments could be expanded to explore agricultural sector development pathways.
- Climate vectors other than precipitation and temperature are affected by climate change – and in turn, affect crop production potential. Pest expansion models that study climate-induced propagation is one such example, which are often not linked with mainstream IAMs. Impacts of pests and plagues can be significant and not only expressive at smaller scales but also propagate internationally via agricultural trade.
- While many IAMs account for temperature and precipitation on crop production, not all account for, in an inclusive manner, effects on livestock (meat and milk production) or fisheries along with food trade. These might be similarly critical given the growth in demand for meat, fish and dairy products; and exacerbated by extreme events such as droughts, floods and storms – climate extremes that are not easily captured by IAMs.
- Looking across key sectors and their nexus, it appears as though much agricultural infrastructure might be quickly deployed in the face of climate shocks. (Of course, others – such as reforestation can take time). It may be the case that when designing an arsenal of options to adapt to climate change from a 'whole society' perspective, agriculture might provide quick critical wins and thus could be prioritised. Consider for example electricity generation infrastructure as an alternative; it is long-lived—and risks being stranded if investments choices are not adaptive nor robust. This hypothesis, however, is not tested—though it should be—given the importance of gearing up for adaptation in our changing climate.

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- Further, the climatic conditions may be influenced by radioactive fall-out in future catastrophic events. Yet, a clear assessment of potential radioactive countermeasures and emergency immediate-and-longer responses are missing from all global IAMs.

5.4 Agriculture and Land use

Land is used as a resource in many of society's delivery chains. It is also impacted by those chains. As with water, it supports essential ecosystems. Further, it is essential for all non-aquatic agricultural production. Thus, competition for land and arable land, in particular, need to be well understood, as it is a limited resource. Several key areas needed for analysis are identified:

- In order to understand crop, fodder and livestock growth potential, detailed GIS maps are needed with high resolution. The types of maps needed are manifold – and a standard set include agro-ecological zoning (AEZ) efforts carried out by the FAO. AEZ (and constituent maps) exist globally, but some are coarse. Not all are 'ground-truthed' (as they often based on remotely sensed data). Increasing the resolution of these maps and their calibration is important.
- Further, complementary information is needed. GIS Rainfall, runoff and water-table depth maps exist. However, little data is easily accessible for aquifers about their re-charge dynamics and total water carrying capacities. These are critical to understanding the dynamics of potential groundwater irrigation by land location.
- Modelling and related analysis is often delineated by physical land areas including local, national, regional and global boundaries. Methods to reconcile data, information losses (and gains) as we move between scales is important.
- Methods to communicate socio-political considerations associated with land-based agricultural modelling (as both inputs and outputs) are needed. An efficient agricultural system will rely on trade and growing crops where there is the locational comparative advantage to do so. However, a push to increase national food security will skew this and lead to strains on the physical system.
- Finally, there needs to be clearer (and policy-relevant) description of how (particularly) arable land is and might be used (or reclaimed). Key questions include: How much is needed for ecosystems and green infrastructure? How much is needed for urbanisation? How much is needed for energy production? How much desert can be transformed into arable land[4]?

5.5 Agriculture, society and its governance

Society and its economy drive the demand for food, fibre, fuel, feedstock and ensuing refuse from agriculture, depending on preferences, markets, policy among other things. How we manage our societies, and the agricultural value chain has a direct effect on the resources that we use. However, there is important information missing to help, assess and inform policies.

[4] Land-use and special planning need to be revisited. Common signals such as prices drive many decisions, but they might not be enough. Alternatives need to be investigated. The willingness to pay for a spacious lawn and house in an expanding suburb may be far higher than the earnings to be gained, by farming it. Yet, food production and its demand is a hard and growing constraint.

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- Food security is a concern with global dimensions. One policy measure is to increase the efficiency of the food chain from field-to-fork. As reducing waste ultimately reduces the draw on limited resources. However, documentation on waste and food loss is poor (Gustafsson et al., 2013) in integrated assessments.
- Information, interventions and their impacts are routinely represented in models. These are needed to project, predict, prospect, promote and postulate the effect of policies (or the absence thereof). They are vital instruments – and yet they are incomplete. We summarise some shortcomings.
    - Models often represent quantitative physical interactions (even if behavioural). Yet, the policy put in place will affect the extent and efficacy of the action. There is almost no explicit mapping between policy and its impact regarding 'extent' or 'diffusion' of the physical change or the efficacy of that change. An example is efficient irrigation. An information campaign (depending on the context) may move a proportion of farmers generally to more efficient techniques – and be well received. Banning of water-intensive crops and all but drip irrigation will, on the other hand, cause a drastic shift. It might be less well received. An explicit mapping of policy to physical uptake is not available across the agricultural value chain – which necessarily transcends sectors.
    - Further, in the models reviewed, there is not the most explicit representation of what can – and what cannot be easily (and directly) changed. For example, the implications of decreasing precipitation due to climate change is (in the short term), and the introduction of irrigation efficiency measures are not the same; yet these are not at first glance distinguishable. Thus the policymaker (and analyst) does not have a clear picture of what, from their toolkit of options can be invoked. Ensuring that models develop policy-relevant information (rather than simulate potential trends – without distinguishing what can or can't easily be controlled) will be important.
    - Models are configured with different end-goals. Is one 'simulating' perturbations to the system or is one attempting the 'cost optimal' solution to meet different end goals? Depending on the goal, different modelling techniques are used. For the former, a 'systems dynamics' approach would be useful. For the latter, an 'integrated systems optimisation' approach may be more efficient. Yet each has different assumptions, decision rules and advantages. Thus constructing a 'master model' is more complex than simply stitching tools together. It may need a complete redesign—either from scratch in a single model—or the collection of individual 'reduced models' that are linked. Again, no clear mapping exists for the appropriate modelling technique by question for multi-sector systems.
    - Many models undertake global analysis – with global balances. This is important – if the Titanic is sinking, all else is deckchair arrangement. It is essential to know if a growing global population, for example, can be fed. These global models often indicate how best to make use of the comparative advantage.
    - Further, it is unclear that a 'master-model' that includes all interactions is needed, useful or even feasible. Perhaps some simplifications can be made – and certain interactions ignored.
- Modelling efforts are often shaped around upon trends that are in place – and are limited to a specific sector. Evidence has emerged that sectorial policy intervention (as noted in the opening paragraphs) can be "indivisible, reinforcing, enabling, consistent, constraining, counteracting or cancelling" policy goals in another. As moving between sectors, scales and specific goals can be tricky, an enabling environment to build, test and decipher increasingly complex and interrelated systems is lacking and needed. Several fledgeling efforts exist, but they need to be cultivated.
- Further, while the SDGs provide a useful time-bound target, a longer timeframe will be needed to ensure that our development – supported by agriculture – can be sustained. Population growth will continue beyond 2030; climate change impacts are likely to be more severe after this point. Energy requirements will grow, as will water needed. The linkage between these will grow and tighten requiring coherent in-depth analysis, policy and (combined with the short) a long-term outlook.

6. CONCLUSIONS – TOWARDS A COMPREHENSIVE RESEARCH AGENDA

There is a need for a research agenda that clearly defines agricultural interactions with those of other sectors. It should move towards creating a clear understanding of what policies, measures and goals in agriculture have important knock-on effects elsewhere, and vice versa. For the latter, it is suggested that an enabling environment is actively formed to support a broad and sustaining ecosystem of research activities. This is because the range of activities to be carried is extensive—yet they are of critical importance. Biophysical mapping (and modelling) within and between sectors is incomplete. In that mapping, there is no consistent charting of where the system(s) can be manipulated—nor the efficacy of policy to manipulate. This means that there is no clear method to understand if policies within sectors and between sectors are compatible or not. Given multi-faceted challenges such as continued development, resource constraints and climate change, we are ill-equipped to develop an efficient societal response – and articulate agriculture's role. That is not to say that the task at hand is insurmountable. It is not. We suggest simple steps to initiate the change needed. We do so by pointing to specific activities where the agricultural sector is interwoven in the nexus.

Quantify and update energy requirements in agricultural food chains. Specifically, this must be defined in terms of energy services needed (i.e. heating, cooling, processing requirements) with an inventory of methods available to provide that service. (For example, crop drying could be done by burning fuel or with solar heat). **Conversely, quantitative descriptions are needed of how links in those chains can produce energy.** Examples (among a number of others) include harvesting and burning agricultural waste, biogas production from food processing, the use of animal excrement in incinerators and digesters etc. With this information, it is possible to start to harmonize and integrate agriculture explicitly into energy development models and plans. Integrated modelling and planning should have a particular focus in LDCs. Herein agriculture and energy are strongly interwoven. Ensuring access to modern, affordable energy to the one billion without electricity and over two billion dependent on biomass for cooking is a case and a point. Electricity in poor remote areas can (in part) be supplied by the co-generation of electricity for agro-industry and people—often using agricultural waste. As such, the activities mentioned above have the potential to lift incomes and affordability of alternative healthier fuels.

Quality needs to be addressed on par with quantity while addressing agriculture and water system interactions. Along with all agricultural chains (and their respective links), a comprehensive inventory and assessment of water use is needed. This is in terms of input, use and discharge (in its various forms, e.g. evapotranspiration, irrigation return flows etc.). As water availability can be limited and of varying quality, understanding the latter's relationship with each production step is needed. In the case where water quality is adversely impacted, the level of impact and options and costs for remedial action should be documented. In response, an inventory of measures for water management (supply, efficiency measures, etc.) should be compiled. **This should include an active collection of available practices – as such, the knowledge is localized and not diffused**. To understand broader impacts of the former, modelling case studies including of water quality into water quantity models is needed. Associated with such hydrological modelling extensions to include non-standard (i.e. nitrogen and phosphorous) pollution cycles may be needed. **Policy analysis and modelling is needed to better capture macro water management and its tensions.** For example, water infrastructure (such as dams) is often funded by hydropower payments. Yet the scheduling of hydro-power can immensely (and negatively) impact agriculture, as those dams—and downstream flows are needed for irrigation. Thus clear and transparent methods for integrated water-agricultural analysis is needed. And as indicated this necessarily requires some level of energy assimilation.

Consolidate climatic impacts on agriculture (food systems) in a comprehensive manner. There are several key sets of information missing either in terms of data or in incorporating that data into models. For example, there is a need to include CO2 fertilization effects explicitly into adaptation planning. High levels of climate change will (be associated with higher CO2 levels and) require astute and comprehensive adaptation planning – this is not yet widespread. Some climate change induced vectors, not yet included should be included in large-scale models. These include pest propagation - these may have a significant impact under an uncertain climate. Quantified effects of increased salinity and acidification in fisheries need to be incorporated in studies that focus on climatic impacts on food systems. Temperature effects (changes in extremes and general increase) on livestock and fisheries also need a harmonised documentation. Importantly, many climate change impacts are uncertain. Thus**, there is a need to collate, develop and incorporate methods for dealing with this uncertainty into regular agricultural planning** (and not just academic or insurance related assessments). Given its special place in the nexus—and relatively rapid adaptive ability of some of its components—assessments of agricultural adaptation relative to other sectors should be undertaken in order to ensure its (hypothesised) prioritisation. Finally, **climate resilience and adaptation has to be mainstreamed into national planning**. Note, however, that as progressive agriculture, energy and water assessment is argued for in previous paragraphs, for climate adaptation (and mitigation) assessments full integration provides disproportionately important information.

For sensible appropriation of agricultural development into societies, models of integrated development (that include agriculture and other sectors) will be needed. The proposed research agenda, therefore, needs to ensure that those developed models represent what elements therein can be manipulated by policy. **A time delineated quantified assessment of the extent to what specific policy measures affect the model element is to be ascertained.**

A broader issue to be addressed is the potential harmonisation and integration of diverse models. This ranges from developing clear databases for the agriculture sector to understanding what level of detail and integration is required for what question. In the case of the latter, this will require an attribution analysis simulating as much of the integrated system as possible—to understand the potential relative importance of input data. In the meantime, simple harmonisation of policy masterplans as mentioned above should be encouraged.

6.1 Towards an open ecosystem for integrated policy research

To move from adding missing data, to developing new methods of diffusion into policymaking is no easy task. It should not be carried out in isolation. Thus some key elements should be lifted and perused. Along the way, formats and data standards[5] should be developed and propagated - for easy use and uptake by other analysts. This must include encouragement of open access data and open source toolkits. More broadly, an 'enabling environment' around which a research ecosystem can thrive – and be seeded with the challenging research agenda laid out.

An example of an initial research activity that might help seed such an ecosystem is the development of integrated development plans for lighthouse cases. We suggest one order may be to start with:

(1) An integrated agricultural-energy development plan (in an LDC context)
(2) Develop or extend and move to a fully integrated national model to assess climate adaption and mitigation.
(3) No. 2 may lead to quantify SDGs inter-relations – beyond the mapping exercise undertaken in this and other similar works.

In each case (1)-(3), there are strong drivers for the analysis. These might be used to expose and encourage related work. Methods to encourage this might include joint multi-actor activities for inter-sectoral mapping; the development of data standards and setting up systematically themed meetings, journal special issues, nominal research challenges and others.

[5] Important elements of the data standards needed might be to develop consistent definition of agricultural production 'chain' and 'links' within those chains. Ensure appropriate Metadata for data sets (including those that are GIS based).

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ANNEX

https://www.scienceforum2018.org/sites/default/files/2018-10/SF18_Annex_tables_Sridharan_1.xlsx

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