Abstract

Agri-food systems present a fundamental paradox. On the one hand, the global food demand is not being adequately met, with almost one in ten people worldwide facing undernourishment due to a lack of available and affordable food, often associated with low crop productivity in specific regions. On the other hand, large shares of food commodities are lost in the early stages of the value chain (e.g., production and processing) and wasted at the end stages (e.g., households and food services), resulting in an inefficient use of the embedded natural resources. These inefficiencies compromise food security and impose unnecessary pressures on water and other natural resources. In view of future population growth, shifts in dietary habits, climate change, and trade disruptions, there is an urgent need for integrated transformation strategies, to make our agri-food systems more efficient, equitable and sustainable. The reduction of food loss and waste, as well as the expansion of irrigation to support crop productivity, are considered among the most promising actions to tackle agri-food system inefficiencies. In order to integrate actions into strategies, it is necessary to take into account the interconnections within the Water-Energy-Food-Ecosystem Nexus, as interventions can yield co-benefits or trade-offs across its different dimensions. Food systems are profoundly globalised, with trade networks connecting even distant regions, thus creating complex interdependencies and making it difficult to pinpoint delocalised impacts. Strategies must deal with this complexity carefully tailoring actions to the specific agri-food context. Different regions face different challenges, ranging from irrigation that overexploits water resources in some areas to severe irrigation gaps in regions such as Sub-Saharan Africa, and from food losses affecting the supply side of agri-food systems to food waste on the part of consumers.

In this context, this thesis deals with three macro-gaps in literature, concerning (i) the existing limitations in the modelling of food loss and waste at the global level, including their impacts on the Water-Energy-Food-Ecosystem Nexus; (ii) the lack of

regional techno-economic assessments of the economic feasibility and environmental sustainability of solar-powered irrigation in Sub-Saharan Africa and (iii) the scarcely-researched impacts of novel digital companies that target food waste reduction in high-income countries, offering alternative circular consumption models. In the first part of this thesis, the NETFLOW model (Network-based Evaluation Tool for Food LOss and Waste) is presented, a tool able to quantify food loss and waste with unprecedented detail, tracing environmental impacts along global trade networks and disaggregated food value chains. Utilising this approach, we assess the effects of food loss and waste on the Water-Energy-Food-Ecosystem Nexus, covering the vast majority of the global crop production. We uncover the interdependencies between countries whose consumption generates food loss and waste, either directly or indirectly, and those where the Nexus impacts are felt. We then evaluate the potential for reduction, demonstrating the existence of equivalent pathways towards food loss and waste reduction, which deliver similar co-benefits on the Nexus dimensions analysed. In the second part of this thesis, we address the issue of irrigation expansion in Sub-Saharan Africa. We undertake a spatially explicit, techno-economic analysis of solar-powered irrigation for smallholder farmers in rural areas, evaluating the economic viability and environmental sustainability of closing the irrigation gap while ensuring water resources conservation. In the third and last part of this thesis, we present a company-scale case study with *Too Good To Go*, estimating virtual water savings from surplus food sold in Milan and Turin, linking local actions to global environmental benefits. Taken together, these contributions aim to support more effective, integrated strategies for transforming our agri-food systems to achieve global food security and sustainability.