Livestock futures in a changing world: Modelling interactions between animal agriculture and the environment

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Human appropriation of biomass as food, feed and raw material interferes with major biochemical cycles and directly affects around two thirds of the Earth's terrestrial surface. Livestock production is at the epicentre of agricultural material flows and resource use, utilising the majority of the economically used plant biomass, substantially amplifying the agricultural nitrogen cycle, contributing to anthropogenic greenhouse gas emissions and water use, and dominating human use of land. Over the last decades, the livestock sector emerged as one of the main drivers of key environmental problems, arising across scales, regions and production systems. While already today's environmental footprint of livestock gives cause for concern, global demand for meat, milk and eggs is expected to continue growing, driven by population growth, increasing incomes, and urbanization. Between the poles of current environmental externalities and the magnitude of past and expected growth of the livestock sector, this thesis aims at analysing interactions between animal agriculture and the environment in the context of broad-scale developments such as globalization, technological change, lifestyles, population growth and climate change and addresses gaps and uncertainties in our knowledge about current environmental externalities of livestock production. Across several scientific studies, this thesis quantifies environmental consequences of alternative future demand- and supply-side developments in the livestock sector and identifies strategies to reduce agricultural resource use and impacts on the environment.

The methodology of this thesis is based on the concept of economic land-use modelling that fuses spatially explicit process-based biophysical models and agro-economic market models, thereby integrating different scales and scientific disciplines. For this thesis, the global spatially explicit economic land use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) was extended by a detailed representation of the livestock sector. Links between livestock and crop production are established through regional and product-specific feed baskets that evolve with the level of intensification, recycling of nutrients in manure as organic fertilizer, trade-induced re-allocation of livestock and crop production according to comparative advantages, investments in research and development and competition for land and water resources between food and animal feed production.

At present, there is a substantial heterogeneity of feed conversion efficiencies and feed composition across different livestock production systems. Our results demonstrate the large potential of transitions between current production systems to transform biomass flows in agriculture, improve resource use and offset detrimental impacts of climate change on the natural resource base of livestock farming, thus representing an efficient and low-risk climate adaptation strategy. In a second step, implications of productivity gains beyond the level of current local systems are assessed, where increases in livestock productivity do not only improve feed conversion, but also entail a shift from residues, food waste and grazed biomass to nutrient-rich feed, a shift from pasture to cropland and from green precipitation water to blue freshwater. While the potential of productivity gains in the livestock sector to abate deforestation and carbon emissions is large, trade-offs emerge between aquatic and terrestrial ecosystems, and between nitrogen losses and carbon emissions. Moreover, ambitious productivity increases trigger large-scale pasture-to-cropland conversion that involves depletion of soil carbon stocks on agricultural land and thus might jeopardize carbon savings from higher overall land productivity. A reduced consumption of livestock products in affluent regions considerably mitigates deforestation, carbon emissions and agricultural water consumption, but mainly of green origin. Across all investigated scenarios, the most optimistic projection of freshwater use in agriculture still represents a substantial increase compared to current levels.

Although significantly reducing environmental externalities of agriculture and increasing the option space to solve sustainability trade-offs between land and water resources, dietary changes cannot solve the water challenge of future food supply nor halt deforestation and related emissions without dedicated environmental policies. Consequently, preference-based strategies to foster sustainable food consumption patterns need to be combined with production standards and incentive-based schemes targeting producers to tap the full potential inherent in the livestock sector to transform material flows, decrease the agricultural nitrogen cycle, respond to adaptation and mitigation imperatives, and reduce the appropriation of increasingly scarce land and water resources.