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Incorporating Nitrogen in the water-energy-food nexus: an optimization approach

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Growing populations and improved standards of living are spiking the global demands for food. Coping with this challenge, agricultural systems casted unprecedented stress on water, land, and nutrient cycling at all scales. Of those nutrients, nitrogen quickly evolved as a major limiting factor for plant growth up until the discovery of the Haber-Bosch process, which made reactive nitrogen available at an industrial scale. This facilitated intensified agriculture, thus boosting the efficiency of agricultural systems and leading to yields that traditional agricultural practices could not deliver. Unfortunately, this translated into intensified application of nitrogen fertilizers to meet the growing crop yield targets in food production, resulting in excessive reactive nitrogen entering our ecosystem causing detrimental effects on the environment and human health, as well as threatening Earth's resilience. Furthermore, reactive nitrogen production is energy-intensive and generates a substantial energy and carbon footprint. This calls for the development of holistic nitrogen management approaches to limit nitrogen's adverse effects. In this study, we develop a mathematical optimization model for the optimal application of nitrogen to meet an evolving and growing agricultural agenda, under a water-energy-food nexus framework. The model optimizes for nitrogen allocation under sustainable water, food and energy security targets, where the nitrogen planetary boundary is the primary environmental constraint, in addition to other nutritional, socio-economic and natural resources constraints. We attempt to optimize the nitrogen footprint required to meet current and future food demands, taking water, energy and carbon footprints into account as well. We incorporate the nitrogen cycle within the land-crop-food continuum and utilize nitrogen use efficiency as a primary indicator. The model serves as a decision making tool for optimum nitrogen application based on nitrogen demands from optimized agricultural policy. It re-allocates different nitrogen sources (industrial, natural, or recycled) available at the regional scale into the farm scale. The model is validated using a hypothetical case study to test the sensitivity of the nexus and its governing policies to nitrogen use efficiency.