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Perspective

Recent Developments and Challenges in Projecting the Impact of Crop Productivity Growth on Biodiversity Considering Market-Mediated Effects

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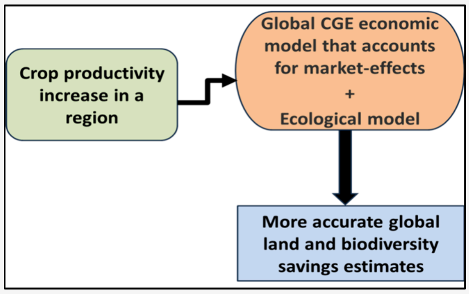
ABSTRACT: The effect of an increase in crop productivity (output per unit of inputs) on biodiversity is hitherto poorly understood. This is because increased productivity of a crop in particular regions leads to increased profit that can encourage expansion of its cultivated area causing land use change and ultimately biodiversity loss, a phenomenon also known as "Jevons paradox" or the "rebound effect". Modeling such consequences in an interconnected and globalized world considering such rebound effects is challenging. Here, we discuss the use of computable general equilibrium (CGE) and other economic models in combination with ecological models to project consequences of crop productivity improvements for biodiversity globally. While these economic models have the advantage of taking into account market-mediated responses, resource constraints, endogenous price responses, and dynamic bilateral patterns of trade, there remain a number of important research and data gaps in these models which must be addressed to improve their performance in assessment of the link between local crop productivity changes and global biodiversity. To this end, we call for breaking the silos and building interdisciplinary networks across the globe to facilitate data sharing and knowledge exchange in order to improve global-to-local-to-global analysis of land, biodiversity, and ecosystem sustainability.



KEYWORDS: *Biodiversity, Trade, Agriculture, Sustainability, Total factor productivity*

1. BIODIVERSITY LOSS: A GLOBAL CAUSE FOR CONCERN

Biodiversity underpins all the provisioning, regulating, and cultural ecosystem services provided by nature to humans,[1] but the rate of loss of global biodiversity far exceeds the background rate of extinction, with anthropogenic land use change being the dominant driver behind these losses.[2−4]

To avert the ongoing biodiversity crisis, the United Nations' Convention on Biological Diversity (CBD) recently adopted the Kunming-Montreal Global Biodiversity Framework (GBF) at the 15th Conference of Parties (COP15) that lays down four long-term goals for 2050 and 23 global targets where the actions set out in each target need to be started immediately and completed by 2030.[5] These targets and goals complement the United Nations' sustainable development goal 15 (Life on Land) that also aims to halt the ongoing biodiversity loss by 2030.[6]

To safeguard species and "bend the curve" of biodiversity loss, there have been growing calls for setting aside land areas for biodiversity conservation with minimal, or no, human activities. Targets 1−3 of GBF relate to conserving or restoring land areas globally to safeguard biodiversity. Some studies have estimated that to meet global biodiversity conservation goals, as much as 44% of the world's terrestrial area requires conservation attention either in the form of them being declared as protected areas or them being managed in a way that is not harmful to biodiversity.[7]

Past studies have estimated that the only way to feed a growing world population with a nutritionally adequate diet without harming the biodiversity is by simultaneously reducing food losses, adopting a planetary healthful diet, and advances in technology to close yield gaps and enable growing more food per unit area in a sustainable manner.[8−13] Target 10 of the GBF also calls for actions to increase the adoption of sustainable intensification[14] as one of the approaches in the agriculture sector to ensure global food security without harming biodiversity.[5]

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2. CROP INTENSIFICATION AND LAND SAVINGS DEBATE

The main driver behind global land use change has been our food system. A majority of Earth's ice-free land is currently used for the purpose of agriculture (crops and livestock production), and ongoing agricultural expansion has been the predominant driver behind ongoing deforestation,[15] resulting in habitat loss, fragmentation, and degradation for native biodiversity and consequently causing their population decline and eventual extinction.[2,16−18]

Boosting yields (or crop intensification) on existing croplands sounds like an intuitive "land saving" solution that can prevent further agricultural encroachment on Earth's remaining natural habitats.[19−22] However, the manner in which such yield gains are achieved can have dramatically different implications for biodiversity. When these yield increases are driven by increases in chemical inputs, for example, biodiversity can be severely compromised.[23−25]

Historically, investments in agricultural research and development have allowed farmers to "do more with less", thereby boosting total factor productivity (TFP: an index of output growth, relative to the growth in inputs).[26] This can provide a vehicle for protecting the environment, even as food production increases.[27] However, in practice, new crop varieties and production techniques have not always benefitted the environment,[28] suggesting the need for a broader measure: "Green TFP", which can account for such negative externalities.[29−31] Developing such measures is an active area of research, currently supported by the Organisation for Economic Co-operation and Development (OECD) as well as many national governments.[32,33]

Here, we focus on the consequences of TFP growth for global land use, cropland conversion, and subsequent biodiversity loss. Does "doing more with less" in one location limit the extent of global biodiversity loss? Answering this question requires a fusion of economics and biodiversity sciences. Central to this question is the role that "market-mediated effects", operating via changing relative costs and prices, play in transmitting developments in one location to those making decisions about production, consumption, and land use elsewhere across the globe.

In the absence of all market-mediated responses (i.e., holding costs and prices constant), a one percent increase in crop yield will reduce the demand for land by one percent, assuming consumption is unchanged—a phenomenon known as the Borlaug hypothesis—coined by the "father" of the Green Revolution who argued that agricultural innovation spares land and nature.[34] However, if this improvement in crop productivity is driven by improvements in TFP (as opposed to increased input usage), this reduces costs and boosts profitability, thereby incentivizing producers to expand the crop frontier into other uses as well as the clearing of natural lands,[35] potentially giving rise to "Jevons paradox".[36] This is termed a paradox owing to the fact that greater efficiency in use of the land can lead to more land being used. Jevons paradox referred originally to the increased use of coal, as steam engines became more efficient during the industrial revolution and has been subsequently observed in many other contexts, including irrigation water demand[37] and national cropland use.[38]

In some cases, though, the Jevons paradox does not arise. For example, as the latter study[38] shows, when agricultural TFP growth is widespread, global prices are reduced, diminishing the incentive to expand cropland area. As a result, there can be substantial cropland savings when TFP growth occurs at the global level (i.e., Jevons paradox or the rebound effect can be absent in cases when crop TFP growth occurs at the global level rather than in a geographically limited locality). Villoria et al.[38] estimate that global TFP growth in agriculture over the period 2001−2010 resulted in 129 Mha less cropland being required, thereby benefiting birds, mammals, and amphibian populations in four of the most biodiverse ecoregions in the world. Moreover, the TFP gain does not always have to be widespread (global) for there to be global biodiversity savings. Rather, we just need the expansion to occur in high productivity/low biodiversity regions so that the expanded production prevents expansion in high biodiversity regions.The market-mediated effects of technological improvements in one region of the world are also highly dependent on the international trading system.[39] Hertel et al.[40] conclude that a prospective (future) Green Revolution in Sub Saharan Africa (SSA) would reduce global land use and terrestrial greenhouse gas emissions if that continent remains relatively isolated in terms of international trade, as has been the case historically. However, in the context of fully integrated global agricultural markets, terrestrial emissions from land conversion would actually increase globally as a result of the improved TFP growth in SSA. They show that this is due to the relatively low ratio of crop yield to carbon stocks in the SSA region, compared to the rest of the world. By displacing more "environmentally efficient" food production with production in the SSA region, global emissions rise. The authors conclude that any such acceleration of TFP growth must be accompanied by protection of the most carbon-rich and biodiverse lands in SSA to avoid this perverse outcome.[40]

3. USE OF ECONOMIC MODELS TO ACCOUNT FOR MARKET MEDIATED EFFECTS

3.1. Lessons from Use of Economic Models in Climate, Water, and Biofuel Domains. The fundamental challenge associated with capturing market-mediated effects of changing crop productivity is that the immediate land use and biodiversity impacts are typically quite localized. These direct, local impacts depend on local land cover, soils, hydrology, and weather, among other factors. Yet the indirect, market-mediated impacts can be felt across the globe. Capturing these impacts poses a significant challenge for economic modelers.

One of the most highly developed areas of application where crop productivity changes play a central role is the case of climate change. Its impacts on agriculture have been extensively studied, using models seeking to capture local impacts, while also integrating global market effects. Baldos et al.[41] explored the global geography of climate impacts, separating the direct climate impacts (reduction in yields) on the four major staple crops (maize, soy, wheat, and rice) from the market-mediated effects of these impacts. They found evidence of substantial sharing of adverse direct climate impacts via international markets. In particular, the increase in export prices by those countries experiencing climate change-induced adverse crop productivity impacts allows exporters to share the burden of climate change with food importing countries. Countries that import primarily from a few sources may be particularly vulnerable to productivity losses in the wake of climate change. The authors highlight the case of

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China's soy imports from Brazil. According to their meta-analysis of past studies,[42] soybeans in the tropics are expected to experience adverse productivity losses from elevated temperatures. And China is increasingly reliant on Brazilian soy imports. As a consequence, the global market impacts of +2 °C warming on China are reversed (they change from positive to negative), and impacts on Brazil are diminished once the international market-mediated effects are taken into account.[41] Similar findings on the role of market-mediated (production and trade) adjustments in attenuating the impact of climate change on welfare are reported by Gouel et al.[43]

Another type of market-mediated adaptation that can shed light on the productivity puzzle is the response to constraints on groundwater abstraction. By limiting the extent of irrigated agriculture, a groundwater sustainability policy can sharply reduce conventional crop productivity in many locations where yields are currently very high. When a groundwater sustainability standard is implemented globally, Haqiqi et al.[44] found that the immediate and direct impact is to reduce global crop production by more than 12%. This, however, in turn, induces knock-on (market) effects through commodity markets which dramatically reduce the final impact on crop production. The higher prices induce on-farm adaptations (e.g., substitution of surface water for groundwater and installation of more efficient irrigation equipment), reversion of irrigated cropland to rainfed agriculture, relocation of production within the country, and international trade. They conclude that, after accounting for market mediated effects, the final impact of a global groundwater sustainability standard on global crop output is likely to be quite small, although the local impacts on production and employment can be dramatic.

Finally, Hertel et al.[45] showed how market-mediated effects modulate the global cropland conversion (indirect land use change) following a policy to increase the annual biofuel (maize ethanol) production in the US. In the absence of market-mediated effects (i.e., assuming unlimited availability of land, labor, capital, and other resources in the world), 15.2 Mha of additional cropland area would be needed for a 50.15 GL per year increase in US ethanol production. However, as resources are finite in the real world, increased ethanol production will trigger a series of market-mediated effects such as increased maize prices, lower nonfood demand, intensification of forestry and livestock activities, use of coproducts for ethanol production, reduced food demand owing to higher prices, and increased yields for croplands. The net cropland conversion globally after incorporating these effects came out to be just 4.2 Mha which is almost a quarter of the 15.2 Mha original estimate that ignored these real-world market adaptations and responses.[45]

The lessons from these climate, groundwater, and biofuel examples underscore the importance of accounting for the market-mediated effects when evaluating the impact of crop productivity increase on land use change and biodiversity. Ignoring market effects while designing agricultural or biodiversity policies can lead to unintended negative consequences for both human welfare and nature.[46]

3.2. Use of Economic Models to Translate Productivity Increase into Land Use Change. There are now a large number of studies focusing explicitly on the interplay between crop productivity growth and land use change. While some have totally ignored market-mediated responses and relied on historical yield growth estimates to project future cropland conversion,[47,48] others have employed partial equilibrium economic models to quantify and project the potential land savings due to technology-driven productivity (TFP) gains globally, taking into account feedback loops, international trade, and responses such as changes in consumer demand with increasing prices of products or increased demand of crops abroad.[49−53] They found that to meet the future global food demand without expanding cropland area entails convergence of crop productivity in developing countries with that of the developed world.

However, a limitation with partial equilibrium models is that they do not incorporate market responses outside of the agriculture sector, thereby missing the chain of effects of intensification on nonfarm incomes and conversely their effects on the agricultural sector via labor and capital markets. Another limitation is that these models often do not include a complete treatment of the land market, as they may neglect nonfarm land use changes such as conversion of managed forests and natural lands to cropland or vice versa.[54]

For a more comprehensive analysis, subsequent studies employed computable general equilibrium (CGE) models such as those based on the GTAP-AEZ model[55] as well as the MAGNET model,[56] that include sectors other than agriculture as well as land markets and have the advantage of taking into account market-mediated responses, resource constraints, endogenous price responses, and dynamic bilateral patterns of trade.[57] The GTAP-AEZ model links economic and biophysical parameters and uses historical patterns of bilateral trade between nations to determine where crop expansion or contraction will take place because of different shocks such as crop productivity increases[57,58] and how much natural land will be converted and used in the economy if land rents (profit from cropland) rise due to increase in productivity. GTAP-AEZ model performance has also been validated in the past regarding its ability to predict crop prices in response to shocks such as technological changes.[46,59] Unlike partial equilibrium models, this model captures the interaction between agricultural and other sectors of the economy. Among others, the main parameters underlying GTAP models are the yield responses to crop price increase, productivity of new pasture or forestry lands is replaced with crops, ease with which pasture or forestry areas can be converted for cropland use, and the ease with which one crop can replace another in a particular region.[57]

The general conclusion of all of this work is that the relation between technology-driven intensification and deforestation mainly depends on the location of intensification (near forest margins or already established areas inland) and the excess demand elasticity for the crop (how sensitive is the demand of the crop to prices, as well as the supply response to this intensification in other regions of the world and the relative size of the innovating region).[40] Productivity increases for a crop with elastic demand (such as palm oil) will increase the likelihood of deforestation, while widespread intensification for crops grown in existing areas with an inelastic demand (e.g., staple crops such as wheat, rice, and maize whose demand changes little with changing prices and incomes) tends to result in land savings.

4. TRANSLATING LAND USE CHANGE INTO BIODIVERSITY LOSS PER REGION

4.1. Cropland Use and Biodiversity Loss. Several factors determine the magnitude of impact of agricultural land use on biodiversity. These include the following: the exact geographical location of land use (e.g., tropical, temperate); its management intensity (e.g., annual crops, permanent crops, organic farms); the degree of land fragmentation, the prehuman potential natural vegetation, and the original biodiversity that existed before the land was converted for agriculture; the ability of existing species in the region to live in the modified (agricultural) settings; the land use matrix surrounding the agricultural farm and on-farm measures for biodiversity conservation (e.g., buffer zones, number of trees).

Many methods have been proposed that quantify the agricultural land use-driven biodiversity impacts using indicators such as changes in species abundance,[60] functional diversity,[61] phylogenetic diversity,[62,63] local species composition/biodiversity intactness,[64] species threats,[18,65] or regional/global species richness.[66]

Substantial advances have been made in the product life cycle assessment (LCA) community in developing so-called characterization factors (CFs; representing biodiversity impact per m^2 of cropland use) by combining ecological models and crop inventory and yield databases.[67−70]

Reviewing the available suite of indicators and methods, the UNEP Life Cycle Initiative[71] and later a research group led by the Food and Agriculture Organization (FAO) of the United Nations[72] recommended the characterization factors (CFs) calculated by the countryside species area relationship (cSAR)[73,74] for use in assessing the impact of land use associated with crop and livestock products on biodiversity. These CFs represent potential species loss per m^2 for five taxa (mammals, birds, amphibians, reptiles, and plants) caused by five different land use types (managed forests, plantations, pasture, cropland, and urban) under three management intensities (minimal, light, and intense use) in the 804 terrestrial ecoregions. These CFs were calculated by combining the cSAR model with the vulnerability score ($0 < VS < 1$) of the species group that represents species' IUCN Red List threat status[75] and their endemicity.[74] The countryside SAR model quantifies changes in species richness because of loss or degradation of natural habitat and takes into account the ability of species to live in both human altered and natural habitats.[74] Unlike other available CFs within LCA, the species loss predicted by cSAR CFs has been validated against the documented ("observed") number of species threatened with extinction on the IUCN Red List, thereby giving them credibility.[73]

4.2. Coupled Economic, Cropland Use and Ecological Models. Several studies have linked the multiregional input output (MRIO) economic trade data with biodiversity indicators to understand the supply chain teleconnections (i.e., impact of food consumption in the importing region on the biodiversity of the producing/exporting region).[65,76,77] Another body of work involves integrated assessment models (IAMs) that have been developed as tools to quantitatively simulate the changes in supply, demand, and trade of commodities of land use and other economic sectors of different world regions as a function of multiple drivers such as changes in population, economic growth, crop productivity, consumption behaviors, globalization, government policies, etc.[78] Some of the popular IAMs that have been widely applied are AIM,[79] MAGPIE,[80] IMAGE,[81] and GLOBIOM. These IAMs, based on partial equilibrium (PE) and computable general equilibrium (CGE) economic models, have been used to obtain alternative future scenarios based on changing the assumptions about the drivers and their outputs can inform policy makers regarding strategies needed at present to achieve the UN SDGs.

The land use modules of these IAMs provide future land use patterns under alternative assumptions such as increased crop productivity. Chaudhary and Mooers[63] were one of the first groups to link six future (2050 and 2100) global gridded land use maps available from different IAMs, representing alternative global warming and shared socio-economic pathways (SSPs), with the countryside species−area relationship model to project the future biodiversity loss for mammals, birds, and amphibians in each of the 804 terrestrial ecoregions and 176 countries and compare them with the current and historical rates of biodiversity loss.

Later through an ensemble approach to model the biodiversity consequences of different scenarios, Leclere et al.[10] used the future grid level land use projections generated by four IAMs and fed them into eight different biodiversity models to evaluate future strategies to bend the curve of biodiversity loss.

Above studies found that the ongoing rate of biodiversity loss can be stemmed only through integrated efforts across demand side (reduced food waste and meat consumption), supply side (increased crop productivity sustainably without increasing farm inputs harmful to species and increasing international food trade), and conservation efforts (increased protected area extent and land restoration).

5. RESEARCH GAPS AND FUTURE RESEARCH FRONTIERS

5.1. Future Research to Improve CGE and PE Performance. One issue with CGE and PE models is that they are often not readily available for use by researchers outside of the group developing the model. This lack of easily accessible, open-access platforms for evaluating the market-mediated effects is one reason for their application. Although efforts are underway to enable running economic models such as GTAP entirely in open-access R language,[82] it still requires extensive user expertise. Another issue is that the data underlying these models are typically not available at fine spatial scale, and thus, their application remains at world regions or at AEZ or the national level only. Finally, these economic models suffer from uncertainties, and hence, their projections must be interpreted with caution. While tools are available for incorporating parameter uncertainty into results from these models, these tools remain underutilized.[83] In addition, they rarely take into account the long-term government policy and political responses to food price increases, land use change, and other impacts.[84] Scenarios, such as the Shared Socioeconomic Pathways (SSPs), are typically used to account for factors like long-term government policy or food price increases. Incorporating probabilistic uncertainty in CGE models is critical for this work to gain broader acceptance in the scientific literature. Future research should devote more effort in characterizing the uncertainty inherent in these model results.

In a new paper by Johnson et al.,[58] the authors combine the GTAP-AEZ CGE model with the fine-scale InVEST modeling suite[85] for ecosystem services in order to assess the impact of ongoing economic growth on the conversion of natural lands and the degradation of four different ecosystem services (pollination, timber provision, marine fisheries, and carbon sequestration). The mediating variables between the InVEST model results and GTAP-AEZ are sectoral TFP growth rates in

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the agriculture, fisheries, and forestry sectors. The authors find that the economic costs of these ecosystem-related productivity losses fall disproportionately on the world's poorest nations. However, the authors also find that a system of payments for ecosystem services, coupled with public investments in productivity enhancing research and development, can result in large improvements relative to the business-as-usual path, accruing annual gains of $US100−350 billion with the largest percentage gains in the lowest income countries.

This work highlights the value of combining fine-scale land use modeling with computable partial and general equilibrium modeling to evaluate alternative sustainability strategies that can be used by policy makers. Extension of such analysis by including multiple indicators of biodiversity and other ecosystem services is an important frontier for future work in this area.

5.2. Future Research to Improve Ecological Models. Most existing models use species richness loss as an indicator of biodiversity loss. More research is needed to enable the coupling of indicators that depict the loss of other components of biodiversity such as phylogenetic diversity (PD)[86] and functional diversity (FD)[61,87] with economic models.[63] This entails increased data sharing, knowledge exchange, and collaboration between scientists from economics, conservation biology, and ecological domains.[88,89]

Currently the land use impacts on species richness of vertebrate taxonomic groups (mammals, birds, amphibians, reptiles) are being reported by authors owing to ease of availability of underlying data from platforms such as the IUCN Red List.[75] However, the impacts on freshwater[90] and marine[91] biodiversity and other terrestrial taxonomic groups such as plants, invertebrates, and fungi are less well understood, and increased investment in field data collection through manual and technological tools is needed to fill this research gap.[92−95]

Even the models quantifying land use driven species richness loss on local, regional, and global scales suffer from several limitations owing to model structure and parameter uncertainties.[64,66,73] Harmonized and validated high spatial-resolution maps of cropland use intensity need to be constructed through collaboration between scientific communities such as geography, remote sensing, Earth, and land system science, that can be fed into ecological models such as the species-area relationship (SAR) to obtain more accurate cropland driven species threat estimates at a finer grid scale than terrestrial ecoregions.[96−98] The area of habitat (AOH) maps[99] of species need to be improved to represent the actual occurrence of individual species across the Earth along with the collection of more information on the affinity (tolerance) of different species to different human land uses with varying intensity levels.[100] Finally, apart from land use and habitat loss driven biodiversity impacts, loss of species due to use of fertilizers and pesticides at the farm level needs to be included in biodiversity assessment in order to obtain a comprehensive picture of the damage caused by crop intensification to global and regional biodiversity.

5.3. The Way Forward. There is growing interest in investments in productivity-enhancing agricultural investments as a vehicle for promoting sustainability.[27,32] However, it is critical that such investments be made with a clear understanding of the potential impacts on biodiversity and ecosystem services. We call for more research on improving our understanding of such impacts.

Current evidence shows that in many cases technology driven crop productivity increases lead to global land savings in aggregate, but deforestation, crop expansion, and thus biodiversity loss might still occur in the locations where the innovations happen. In other words, local land expansion in the face of local productivity growth is offset by land savings elsewhere. In other cases, the estimated land savings due to increased crop productivity after accounting for market-mediated effects are considerably smaller than those calculated without accounting for them.[101] It is therefore increasingly clear that adoption of technologies that improve crop productivity need to be accompanied by strong national land use regulations to have maximum beneficial impact.[102] Sustainable intensification (i.e., without increasing farm inputs that are damaging to species) can be considered as a necessary but not sufficient condition to halt deforestation, land use changes, and biodiversity loss.

This poses a significant challenge to those undertaking quantitative modeling of agriculture, food systems, and the economy, since the drivers of land use change are global in scope, but the impacts are felt at a local level, and the prevalence of biodiversity varies greatly by location. Thus, coupled economic-ecological models capable of capturing global-to-local linkages, as well as taking into account the market-mediated spillovers from one locality to another, are the need of the hour.[103−109]

It is also critical that these models span disciplines, as the consequences of such productivity changes are evidenced in agronomic, hydrological, ecological, and socioeconomic systems—all of which interact to affect the extent of local biodiversity and ecosystem services. For this reason, projects such as GLASSNET (www.glassnet.net) have been initiated which aim to break the silos and build interdisciplinary networks across the globe to facilitate improved global-to-local-to-global analysis of land, water, and ecosystem sustainability. We invite others to join us in this initiative!

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Author Contributions

A.C. conceived the research presented in this Perspective. A.C. and T.H. contributed to the research, analysis, and writing.

Notes

The authors declare no competing financial interest.

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Biography

Dr. Abhishek Chaudhary is an Assistant Professor of Environmental Engineering and Management at the Indian Institute of Technology (IIT) Kanpur. His areas of research include Environmental Life Cycle Assessment (LCA), Biodiversity Conservation, and Sustainability Data Analytics. He has published over 60 peer-reviewed scientific articles in international journals fetching over 12,000 citations so far. Prior to joining IITK, he held doctoral and postdoctoral researcher positions at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland and worked at the United States Environmental Protection Agency (EPA) from 2009–2012 as an Environmental Engineer. Recently, he was recognized as "2022 Rising Stars in Environmental Research" by the American Chemical Society and received an honorable mention at their 2023 James J. Morgan Early Career Award. The goal of his research is to quantify the impacts of everyday products and human activities on multiple domains of the environment and identify ways to reduce these impacts without jeopardizing the social and economic dimensions of sustainability.

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