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The Role and Use of Mathematical Programming in Agricultural, Natural Resource, and Climate Change Analysis

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Abstract

Climate change undeniably impacts agriculture and natural resources, enterprises and markets. For informed decision making, there is a need for information on climate change adaptation possibilities and mitigation alternatives. Mathematical programming has been used to address the economic aspects of such questions and allows analysis as climate change moves the environment into previously unobserved conditions. It allows us to model spatial and dynamic features of the issue and analyze heretofore unobserved adaptation and mitigation possibilities. This review provides an overview of and references for modeling techniques, conceptual issues, and major assumptions involved with using mathematical programming as a climate change economic analyzing engine, along with a brief comparison with other methods. We also review a number of studies applying mathematical programming to examine climate change impacts, adaptation, and mitigation issues in the agricultural and natural resources arena. Finally, we present a very brief discussion on research needs.



1. INTRODUCTION

The climate is changing, with the Intergovernmental Panel on Climate Change (IPCC 2014, p. 55) calling the next 25 years or so the “era of committed climate change.” During that period, projections show there will be about 1°C of warming regardless of mitigation efforts. This means agricultural and natural resource management (ANR) will undoubtedly be impacted and need to adapt (McCarl 2015, Rose & McCarl 2008). Furthermore, later in the century, mitigation does make a difference, and thus we face the issue of how agriculture might participate in greenhouse gas (GHG) mitigation. This combination of climate change impacts, adaptation, and mitigation needs raises the following agricultural analysis issues: (a) What ANR activity is likely to be affected and where? (b) How can the ANR sectors adapt? (c) What actions might ANR undertake to help mitigate? For further identification of these issues, readers are directed to McCarl et al. (2016), McCarl & Hertel (2018), and McCarl & Schneider (2000).

Numerous studies have addressed the ANR aspects of the above issues. A wide variety of tools have been used. Among them are mathematical programming approaches. This article focuses on mathematical programming approaches and identifies methods, key findings, issues examined, and some possibilities for future research, along with a discussion of strengths and weaknesses comparing mathematical programming with other methods for application.

2. THE CHALLENGE OF MODELING IMPACTS, ADAPTATION, AND MITIGATION

Addressing ANR climate change impacts, adaptation, and mitigation raises many considerations influencing the methodological approach for conducting analyses. Here, we briefly discuss these.

2.1. Impacts

Climate change alters the ANR environment, affecting crop yields, livestock performance, pests, wildfires, and surface water availability. The effects vary across crops and livestock types as well as regions. This introduces the need to model (a) a wide variety of crops and grass growth responses where some varieties can perform better under hotter or altered precipitation conditions, (b) a broad set of livestock breeds and animal species productivity responses, and (c) regional disaggregation to reflect varying responses. Climate change also affects regional natural resource systems, such as water availability and grazing supplies. In analyzing major climate change effects, multi-species and multi-regional impacts need to be considered, including impacts on yields, water use, wildfire/pest/flooding/waterlogging incidence, production costs, livestock feed availability and appetite, water availability, invasive species, market price, demand/supplies from other regions, and labor productivity.

2.2. Adaptation

Climate change impacts have implications for adaptation needs and analyses. The cross-regional impacts of climate change on various crops, livestock breeds and species, and natural resources shift production possibilities and relative resource prices. This alters crop/livestock mix choices and management possibilities. The adaptation strategies can include but are not limited to (a) more or less irrigation, (b) more or less pesticide use, (c) shifting varieties of crops/livestock toward ones with more drought or heat resistance, and (d) altering crop management and land use to accommodate altered productivity, conserve moisture, and maintain soil organic matter. Given that climate change is continuing and adaptation has been widely observed (see the documentation in the IPCC

reports), current observations on production systems and enterprise mixes may not be relevant in the climate change–altered future. Production system changes may well move us outside the range of currently observed production systems and management practices. We have seen climate change influences on latitude and elevation shifts in US crop incidence (Cho & McCarl 2017, Reilly et al. 2003). Therefore, adaptation analyses need to consider regional possibilities that have not been historically observed, including technologies, varieties, species, pest threats, cropping possibilities, livestock species/breeds, irrigation possibilities, and pest treatment methods.

Adaptation extends beyond agricultural production processes to supporting industries and infrastructures. For example, Cho & McCarl (2017), Reilly et al. (2003), and Wang & McCarl (2021) show northern and western movements in crops and cow-calf production, while Attavanich et al. (2013) show that climate change alters logistical demand, with changes in needs for rail and barge facilities, and changes in barge versus rail volumes. Also, ongoing work by Carpenter et al. (2022) shows evolving changes in grain processing and livestock slaughter plants. Climate change effects on labor productivity and availability may also influence the harvest systems employed and mechanization extent (de Lima et al. 2021). Finally, altered regional precipitation may lower water supplies, causing enterprise mix shifts toward dryland production and grazing (Cho & McCarl 2021) along with increased irrigation. Additionally, regions with increased precipitation may need to add drainage to address waterlogging.

Overall, climate change adaptation analyses must address the challenges of adding regionally new climate change–induced cropping possibilities, crop mixes, and livestock species/breeds; moving crop and livestock processing; altering irrigation; adding drainage; and so on. This will involve the migration of production systems as well as the inclusion of heretofore unused agricultural production processes.

2.3. Mitigation

ANR climate change mitigation also raises additional modeling issues. In most regions, GHG emissions have been an unpriced externality. Internalizing or alleviating the externality will stimulate ANR management responses. We discuss these in broad classes below following the scheme developed by McCarl & Schneider (2000), plus we add an additional class to cover the increased incidence of agriculture as an energy producer, encompassing solar and wind facilities on agricultural lands and land demands for bioenergy feedstocks.

First, agriculture may take action to reduce emissions directly, for example, by reducing (a) nitrogen fertilizer use, (b) fossil fuel use in mechanical operations and grain drying, (c) methane emissions from livestock enteric fermentation, (d) methane emissions from manure, (e) rice methane emissions, (f) transportation movements of products, and (g) emissions from land use change and deforestation.

Second, agriculture may increase carbon sequestered in soils and long-lived vegetation. This can take the form of (a) decreasing tillage intensity, (b) increasing organic inputs to soils, (c) storing carbon through soil incorporation of substances like biochar, (d) increasing carbon stored in trees or multi-year perennials, (e) increasing planting of deep-rooted species, (f) reducing land use change and deforestation, or (g) moving croplands into trees and grasslands.

Third, agriculture can produce commodities that can substitute for emission-intensive products. Generally, this refers to producing feedstocks for bioenergy. But it can also involve replacements for building products like steel or concrete.

Fourth, agricultural actions can be influenced by altered input price effects caused by broader mitigation efforts. For example, mitigation actions can raise fossil fuel prices and thus lift the costs of ANR production. Prices of fertilizer, pesticides, and transport-intensive input could



also be changed. Collectively this would stimulate adjustments in input use, energy conservation investments, enterprise mixes, and production costs.

Fifth, societal quests for low-carbon fuels may increase the incidence of solar and wind facilities on agricultural lands and land demands for bioenergy feedstocks.

More generally, ANR mitigation considerations raise the need to model previously unused production practices that (a) reduce emissions, (b) increase sequestration, (c) increase bioenergy or building supply feedstock production, (d) conserve the use of higher-priced fossil fuels or emission intensive inputs, and (e) divert producing lands to low-carbon energy production. Antle & McCarl (2002) show that such activities require incentives, as many possible ANR mitigation practices have not been used for economic reasons. Such incentives may take many forms, including (a) carbon market sale possibilities, (b) carbon taxes, (c) higher prices for biomass feedstocks, (d) technology subsidies, (e) new technology standards, and (f) conservation subsidy programs. Therefore, modeling mitigation requires augmenting the production possibilities set to include new practices and adding incentive programs and other policy means to agricultural models.

3. TOWARD AN ANALYTICAL FRAMEWORK

Before fully turning to mathematical programming, we first present separate climate change analysis frameworks for effects and adaptation and for mitigation issues. We also cover why a mathematical program might be desirable to use as the central economic model in the frameworks and what major assumptions and weaknesses arise from its usage.

3.1. Effects and Adaptation Analytical Framework

Figure 1 shows a conceptual framework for ANR effects and adaptation analyses. The principal elements involve a central economic model (nominally the mathematical program), which is solved given a climate change scenario and projections on physical and other effects. That central model chooses among possibilities for crop and livestock management, land use, resource usage, crop mix, livestock mix, irrigation alternatives, trade volumes, consumption, associated prices, and many

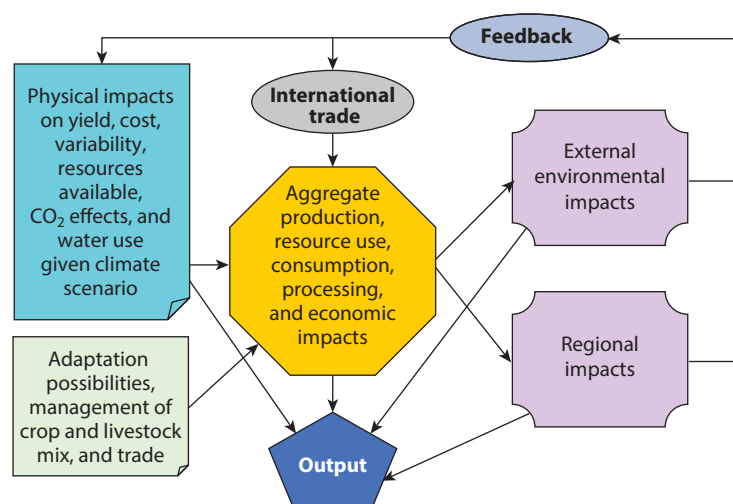


Figure 1

An analytical framework for modeling climate change effects on agricultural and natural resource management and the choice of adaptation actions.

other things. When considering climate change impacts, it is necessary to simultaneously allow adaptations.

In **Figure 1**, the physical effects include projected climate change and associated carbon dioxide implications for crop and livestock yields, irrigation water needs, costs, labor productivity, resources available, resource needs, and pest damages/expenses, among other factors. Typically, such estimates come from some mixture of process simulators like crop models, econometric estimates over historical and experimental data, and expert judgment. Beyond that, adaptation possibilities need to be modeled, covering (a) alternative crops and livestock management strategies, (b) crop and livestock mix possibilities, and (c) pest treatment method alterations.

Following the model solutions with and without climate change, there is a need to portray impacts on regional economies and potentially the effects on shifting needs for infrastructure along with environmental impacts—e.g., water runoff, groundwater depletion, GHG emissions, and soil erosion.

3.2. Mitigation Analytical Framework

Most of the framework for mitigation analysis is the same as above. However, we need to add mitigation alternatives along with their cost, yield, and GHG emission/sequestration implications (**Figure 2**). This includes possibilities for altered soil management/tillage, irrigation, pest treatments, crop and livestock management, fertilization, diet quality to manage enteric fermentation, land use changes to forest and grasslands, feedstock production for bioenergy, and shifted product movement. We also need environmental modeling of items like fertilizer runoff rates and soil erosion alterations.

Beyond that, the model also needs to include dynamic implications of strategies. For example, soil carbon sequestration generally exhibits diminishing gains over time, with net sequestration depending on the time since the tillage method or land use change was first applied (see West & Post 2002 for evidence). The framework also includes policy considerations, such as mitigation incentive design, addressing questions such as (a) who is eligible for payment, (b) what the

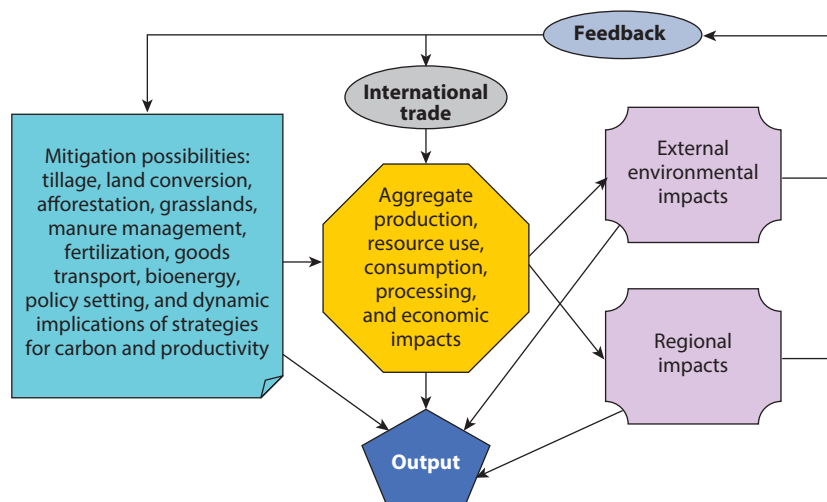


Figure 2

An analytical framework for the modeling of the implications of and choices among climate change mitigation alternatives.

baseline without practice amount is, and (c) how additionality, uncertainty, permanence, leakage and transactions costs are treated (see discussions of these issues in Murray et al. 2005, 2007; Post et al. 2009). Additionally, the framework can potentially cover alterations in extraregional trade, goods transport, and resource endowments.

3.3. The Benefits of Using a Mathematical Program

Fundamentally, a mathematical program optimizes a specific objective expressed as a function of a set of variables, subject to a family of constraints that impose resource endowments, minimum requirements, and supply–demand balances, among other conditions. First, the constraints and variables are often defined on a regional basis and include using multiple resources with linkages between crops and livestock, reflecting crop usage for feeding livestock. They can also include various alternatives for how resources are used to produce goods, reflecting an array of crop and livestock production possibilities. Models can also contain alternatives for processing—for example, raw agricultural commodities can enter processing to make products like biofuels, sugar and sweetener substitutes, soybean meal and oil, and mixed feeds. The inclusion of alternative production and processing variables allows different production possibilities using alternative input mixes. Thus, a mathematical programming model can represent an array of ways to achieve climate change adaptation and mitigation. Also, climate change–induced changes in resource availability, competition, and usage trade-offs can be represented. Additionally, adaptation and mitigation alternatives that have never been used before can enter the solution due to the influence of relative prices and/or incentives falling well outside historical observations.

Second, region-specific climate change and other impacts can be imposed on yields, water usage, water supplies, pests, death rates, etc., as can altered rates of soil carbon sequestration and GHG emissions. In such a case, there may be climate change benefits in production systems limited by cold but damages in those limited by heat. This has been found to induce shifts in crop and livestock mix and land use changes (Cho & McCarl 2017, 2021).

Third, underlying data can be some mix of (a) cross-sectional and time series observations, (b) observations arising from agronomic experiments, (c) data from other locations that are assumed to be representative of what would happen in a given location when it becomes hotter, (d) data from expert opinions, (e) data from crop simulation models simulating performance under conditions that have not been observed, and (f) theory-based assumptions on input usage responses to yield changes and demand/supply elasticities.

Fourth, a dynamic modeling framework allows important changes over time in climate change and mitigation implications. For example, the consequence of adopting conservation tillage on carbon sequestered is not constant over time but varies depending on the time since the tillage switchover occurred. More generally, dynamic modeling can represent things like trees growing to maturity, optimized tree and crop rotations, and evolving climate change shifts in production yields, and it can use input results from dynamic climate change projections.

Fifth, infrastructure asset fixity can be represented through constraints, where once-constructed assets, like biorefineries or planted trees, limit our ability to adapt or mitigate due to capacity and time until obsolescence. For example, Wang et al. (2019) show that the existence of ethanol plants designed to handle specific feedstock classes dampens fluctuations in regional feedstock production.

Sixth, resource usage and endowments can be shifted. For example, to implement a constraint that water usage must be in an amount less than is available, the model can include projections from hydrological simulators and nonagricultural water demand forecasts (Fei et al. 2022). Similarly, the model can reflect changes in land availability due to urban encroachment, land degradation, and desertification.

Seventh, imperfect substitution among resources within production enterprises is represented. For example, crops are mainly limited to croplands, livestock primarily uses grasslands, and grasslands have quite different productivity.

3.4. Assumptions and Limitations

When mathematical programming is used, some major considerations and assumptions relative to other modeling techniques are worthy of mention.

First, the mathematical programming objective may be profit maximization or cost minimization but also may be an objective function designed to simulate the economy, like maximization of producers' and consumers' surplus. In the latter case, the first-order conditions represent a perfectly competitive economy where atomistic price taking producers and consumers operate (McCarl & Spreen 1980). Also, in many cases, the objective function neglects relevant considerations such as risk preferences, historical knowledge of growing crops, and the ability to change equipment rapidly.

Second, the constraints generally limit production and define a convex space of possible production choices, with the objective function picking out optimal actions according to the objective function. Often in aggregate models, there is no modeling of the seasonal availability of resources, which can lead to excessive specialization in results (see Baker & McCarl 1982, Musser et al. 1986). In some cases, this is addressed with adherence to crop mixes (McCarl 1982) or assignment of cost terms (Fajardo et al. 1981, Howitt 1995) reflective of missing information.

Third, production in the model arises as a function of coefficients often assumed to be certain and constant in terms of returns to scale, which may not be reasonable.

Overall, the biggest issue is that one assumes that mathematical programming adequately constructs an estimate of producer and consumer response to a situation based on the specified objective function and constraints along with the nature of the variables included. It differs significantly from econometric models, which construct responses based on historically observed responses and do not need to make assumptions about motivating factors and the adequacy of representing the supply relationship but do assume the future will be like the past, which may not be true in a climate change-altered world.

Finally, we should mention that mathematical programming formulations require substantial data and accurate specification of production yields and resource usage, as well as a set of production possibilities, both now and under adaptation and/or mitigation as they evolve with climate change.

4. A GENERAL MATHEMATICAL PROGRAMMING MODELING FRAMEWORK FOR CLIMATE CHANGE ANALYSIS

Now suppose that we discuss a general mathematical programming model structure for climate change analysis. In this case, we portray several features from the agricultural part of the Forestry and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG) model, adapting and simplifying material (Adams et al. 2005). Here we emphasize features for modeling climate change impacts, adaptation, and mitigation. We do not use forestry or dynamics and direct readers desiring such coverage to Adams et al. (2005) for additional details.

We organize this presentation around the **Figure 3** matrix layout of the FASOMGHG agricultural model component tableau.

4.1. Variables

The FASOMGHG model (Adams et al. 2005) employs the following variables (also shown as the column headers in **Figure 3**):

	Initial tillage choice	Change tillage	Crop production	Livestock production	Manure management	Feed blending	Crop mix	Livestock mix	AUM supply	Water supply	Labor supply	Cropland to pasture	Pasture to cropland	Processing	Domestic demand	Export demand	Import supply	Domestic transport	International transport	GHG payment		Right-hand side parameter
Welfare			-	-	-				-	-	-	-	-	-	+	+	-	-	-	+		
Cropland available	+1											+1	-1								≤	+
Tillage supply by type	-1	+1/-1	+1																		=	0
Pastureland available				+								-1	+1								=	+
AUM grazing supply				+					-1												=	0
Maximum public AUM								+1													≤	+
Water supply			+							-1											=	0
Fixed price water available									+1												≤	+
Labor supply			+	+							-1										=	0
Family labor supply											+1										≤	+
Primary product balance			-	+/-		+								+	+1	+1	-1	+1/-1			≤	0
Secondary product balance				+		+								+/-	+1	+1	-1	+1/-1			≤	0
International market																-1	+1		+1/-1		≤	0
Manure management				+1	-1																=	0
Crop mix			+1				-														=	0
Livestock mix				+1				-													=	0
GHG balance	-	-	+	+	-					+		-	+	+/-				+	+	-1	=	0

Figure 3

Tabular structure of a general agricultural model that can represent effects, adaptation, and mitigation for a single period and region. Abbreviations: AUM, animal unit month, GHG, greenhouse gas.

- Initial tillage denotes the initial tillage in use by region. Adams et al. (2005) use available cropland and supplies tilled the land for use in the crop production variables. They add sequestration amounts in the GHG balance equations based on results from a crop simulation model. Cost is modeled in the crop production variables.
- Change tillage refers to the possible tillage changes by region that reflect the dynamic increment in sequestered carbon-based CENTURY model simulations (Parton 1996).
- Crop production represents crop production possibilities by region and crop, including multiple management alternatives. In FASOMGHG, the alternatives include fertilization, tillage, irrigation/dryland, adaptation, and mitigation possibilities. They use tilled land, water, and labor while producing crop products. They also require land usage that falls within the allowed crop mixes and enters the GHG balances for fossil fuel emissions, nitrous oxide emissions, and sequestration alterations. They include cropping on marginal land.

- Livestock production depicts the regional livestock production possibilities by animals. They use pastureland and/or animal unit month (AUM) grazing and labor while producing livestock products. They also use some crop products directly as feed inputs, processed feeds, and intermediate animals (e.g., feeder pigs, dairy calves, and beef calves). The regional animal distribution must fall within the specified livestock mixes. They also make animals available for manure management and feeding alternatives for enteric fermentation management. They generate GHG emissions from fossil fuels, enteric fermentation, and manure.
- Manure management gives choices of regional improved manure management systems. At a cost, manure-related emissions can be offset in the GHG balance. These variables are defined for feedlots, dairy, and hogs with a step function derived from US Environmental Protection Agency data.
- Feed blending gives options for how the livestock feeds are blended, providing alternative nutritionally adequate formulae utilizing crops and processing byproducts by region.
- Crop mix denotes the choice between regionally historically observed irrigated and dryland crop mixes and a set of climate change–altered crop mixes. They implicitly represent much more detailed, but unobserved, farm-level resource constraints and other considerations, as argued by McCarl (1982) and Önal & McCarl (1991).
- Livestock mix gives choices for the regional distribution of animals to fall in the domain of historical observations. Like the crop mix constraints, they implicitly represent many omitted resource constraints and other considerations. They shift with climate change.
- AUM supply represents the regional supply of grazing on an AUM basis from public and private land sources.
- Water supply represents regional supply of water from fixed-price public and supply schedule pumped sources.
- Labor supply provides the regional supply of labor from family and hired sources.
- Cropland to pasture depicts regional land use change from cropland to pastureland. GHG sequestration accumulates on a dynamic basis when the land use changes.
- Pasture to cropland permits regional land use changes from pastureland to cropland. Carbon sequestered drops immediately from the pasture basis to the cropland basis.
- Processing represents the amount of regional processing activity that transforms crop and livestock commodities into secondary commodities, mixed feeds, and byproducts. The processing variables enter the GHG balances reflecting GHG emissions from inputs used in the processing and GHG offsets when the processed products replace items like highly emitting fossil fuels, as in the case of bioenergy. The processing variable is also bounded by capacity for the operation of bioenergy facilities and reflect capacity construction, as discussed by Wang et al. (2019).
- Domestic demand represents the domestic consumption of primary and secondary commodities. These variables are defined by commodities on a national basis but with regional price differences.
- Export demand represents exports of goods and is specified with either the explicit rest-of-world excess demand equations or country-level demand curves within a multi-country spatial equilibrium model (Takayama & Judge 1971).
- Import supply represents the imports of commodities and is specified with either the explicit rest-of-world excess supply equations or country-level supply functions in a multi-country spatial equilibrium model (Takayama & Judge 1971).
- Domestic transport refers to the domestic transport of commodities between US market regions and ports.



- International transport represents the international transport of commodities between the United States and foreign countries/regions and between foreign countries/regions.
- GHG payment introduces the carbon market payments or charges on a regional basis relative to a baseline level. There is also a global warming potential factor added to convert the alternative gases to carbon dioxide equivalents.

4.2. Objective Function

The objective function is the welfare equation in the model (**Figure 3**, top row) and adds the agriculturally related net present value of consumers' and producers' surplus. It includes the areas under the commodity demand curves minus the area under the supply curves for factors and inputs, minus many production costs and plus a GHG term.

4.3. Constraints

The FASOMGHG model employs the following constraints (shown as the row headers from the second row down in **Figure 3**):

- Cropland available limits the maximum cropland availability by region.
- Tillage supply by type restricts the initial use of cropland by region, tillage practice and irrigation.
- Pastureland available limits the maximum pastureland use to the inventory by region for both suitable cropland and other pastureland.
- AUM grazing supply balances the regional grazing use with the supply of western US grazing land on an AUM basis.
- Maximum public AUM restricts the maximum regional amount of public grazing land.
- Water supply balances regional irrigation water use with supply.
- Fixed price water available limits the regional use of publicly leased irrigation water.
- Labor supply balances regional labor use with the supply from hired and family sources.
- Family labor supply limits regional family labor use.
- Primary product balance imposes regional supply and demand balances of regional raw crop and livestock commodities. The equation includes incoming and outgoing transport, processing, domestic consumption, exports, and imports. It also portrays the use of young animals in stocker, feedlot, and pig finishing operations.
- Secondary product balance imposes regional supply and demand balances for processed agricultural commodities. The entries depict the usage of mixed feeds by livestock production, supply of processed commodities from agricultural processing, direct use of intermediate commodities like cornstarch in high-fructose corn syrup manufacture and feed blending. The equation includes domestic consumption, exports, imports, and interregional transport.
- International market imposes supply and demand balances for the major commodities in each international trading region. It also balances US excess supply and demand for minor commodities.
- Manure management constrains regional animals placed in advanced manure systems with the number of animals available for placement individually for hogs, dairy and beef feedlots.
- Crop mix requires regional acreage by crop in a region to be a convex combination of allowed cropping mixes (see discussion in McCarl 1982, Önal & McCarl 1991). The crop mixes may reflect climate change-induced alterations (Adams et al. 1999) or other adjustments based on expert opinion (Chen & Önal 2012, Schaible et al. 1999). The equation covers irrigation

and dryland mixes. This is only done for crops that use more than 2% of regional land, with minor crops subject to upper and lower limits.

- Livestock mix requires the distribution of the regional herd by animal type to equal a convex combination of historical occurrence across regions. Also, only herd shares above 2% are modeled this way, with upper and lower limits for small herd shares.
- GHG balance adds up regional GHG net emission volumes. These equations incorporate sequestration in soils, biofuel offsets, and emissions. Crop production–related emissions include (a) fossil fuels used in tillage, planting, harvesting, irrigation, drying, and other machinery operations; (b) nitrogen fertilization; (c) rice methane; (d) fertilizer and pesticide manufacture; (e) residue burning; and (f) nitrogen-fixing crops. Livestock-related emissions include (a) fossil fuel usage, (b) enteric fermentation, and (c) manure management. Two forms of the GHG balance equation can occur. One involves the amount of each GHG that is eligible for payment in terms of the improvement after subtracting a regional baseline (McCarl & Schneider 2001, Murray et al. 2005). The other takes a reference practice and pays for the incremental net emission reduction relative to that practice (Wang et al. 2021).

5. SOME MODEL SETUP CONSIDERATIONS

Several major procedures are used to accommodate sectoral-level analysis in mathematical programming, and here we provide an overview and references.

5.1. Price Endogenous Formulation

Climate change is a global phenomenon, meaning it influences not only local productivity (at the focal farm, region, state, or country) but also productivity in other regions, along with interregional trade and market price signals. Indeed, climate events such as the 2022 drought and heat waves influence commodity prices and aggregate commodity quantities available. Thus, we feel ANR climate change analyses across the impacts, adaptation, and mitigation spectrum should employ price-endogenous programming approaches (McCarl & Spreen 1980) to represent how climate change influences aggregate production and the resulting market prices. For example, if climate change reduces production, then higher prices will result. In turn, profit maximizing farmers might revise their production choices to respond to altered prices and production conditions. The price-endogenous formulation includes local demand and supply relationships for commodities, resources, and possibly labor, along with excess supply and demand from external regions.

5.2. Aggregation

Aggregation issues are often encountered in regional- or national-level ANR climate change analyses. Generally, such models contain representative farm models for classes of farms, as there are far too many farms to allow the explicit representation of each. Studies have derived conditions for the representative farms that, if satisfied, eliminate aggregation bias. However, these are practically impossible to meet (see the discussion and literature reviewed in Spreen & Takayama 1980). Consequently, there have also been suggestions and evaluations of strategies to minimize or reduce bias. These have resulted in a basic approach and two means to calibrate the resultant model. The basic approach is related to suggestions in a branch of the literature reviewed by Buckwell & Hazell (1972) that involves grouping firms into technologically similar clusters. This has often resulted in regional groupings of dryland and irrigated farms, sometimes by major enterprise type, along with livestock farms by enterprise type. Beyond this, there are methods that try to match



up regional production with observations by adding either (a) nonlinear cost terms (this is the positive mathematical programming approach developed by Howitt 1995) or (b) constraints that require model variables to fall within an observed convex combination of observed choices (i.e., crop mixes). The former is added to make up for missing costs and nonlinearities in response. The latter is added under the argument that historical choices reflect unobserved considerations that caused those choices to occur (see discussions in McCarl 1982, Önal & McCarl 1991). For climate change analysis, we use the second approach, as the first one limits mitigation and adaptation possibilities by favoring a solution with the pre-climate change acreage allocation.

5.3. Meeting the Market: Profit Calculation

When optimized, the first-order conditions for price-endogenous mathematical programs require that price equals marginal cost. However, when one assembles regional crop budgets and prices, the marginal cost typically differs from the price for several reasons. First, models depict regional commodities as homogeneous. However, prices often vary, reflecting the timing of sales, commodity quality, and varietal differences (consider wheat, which has several major forms exhibiting different prices). Second, the crop production data are often only available for average or typical regional operations due to USDA or others' confidentiality agreements with data sources, and more detailed data sets are unavailable. Price data are typically averaged over sale points, sale times, and grades, as are purchaser price data. Third, market-meeting transaction costs are often omitted. Many models are built from extension farm budgets but use consumer- or regional-level average prices. Handling and transport costs are incurred in the marketing channel that are frequently not present in budgets, nor are spatial and market access differences. Consequently, there are gaps between prices and marginal costs, and modelers have addressed this by adding additional costs. Fajardo et al. (1981) added a cost equal to the difference between farm budget-based marginal cost and regional price. The Positive Mathematical Programming approach (Howitt 1995) also adds a nonlinear cost term amounting to that difference divided by the observed volume.

5.4. Partial Geographic Coverage

Climate change is global, but in many cases, a climate change analysis will focus on a region or country. In such cases, climate change will affect not only the region at hand but also other regions and industries globally. As such, when doing a climate change analysis, one must look at both effects in the focal region and signal transmitted from elsewhere, such as impacts on excess supplies and demands for factors and commodities.

6. AN OVERVIEW OF MATHEMATICAL PROGRAMMING-BASED CLIMATE CHANGE-RELATED ANALYSES

Now we turn to a brief overview of mathematical programming-based studies that have addressed issues across the ANR climate change impacts, adaptation, and mitigation domains. In doing this, we primarily rely on references by this article's authors due to limitations of length, references, and time.

6.1. Climate Change Impact Studies

The first mathematical programming-based efforts on climate change impacts involved a study by a team including McCarl and Adams and were published as Adams et al. (1988) and Adams et al. (1990). The analysis involved using climate change physical effects from corn, soybean, and wheat crop simulation models, with other crops proxied by the average yield sensitivity of those crops.

The study solved the model under base and climate change scenarios, then summarized the results on differences in welfare and cropping patterns, among other outputs. The basic conclusion was that US agriculture would not be greatly damaged by climate change.

Subsequent work extended that analysis in several different ways. First, climate change effects on irrigated and dryland cropping were examined, coupled with carbon dioxide effects, alterations in irrigation water needs, and climate change-affected water supplies (Adams et al. 1995). Then Adams et al. (1999) added heat-tolerant crops (cotton and sorghum) along with effects on live-stock weight gain, resulting in climate change becoming marginally beneficial to US agriculture. Adams et al. (1999) also included a relationship between yield change and input usage (i.e., lower yields need less fertilizer). A subsequent extension addressed changes in the probability distribution of yields based on crop simulator output and utilizing a mean preserving spread, although the effects were small (Lambert et al. 1995). Later, mathematical programming used during the 2001 US National Assessment incorporated climate change effects on grazing/pasture supply, altered livestock feed usage, changed pesticide use cost, and shifted prices from international trade (Reilly et al. 2003). Adams et al. (2003) also investigated the effects of using finer-scale information in terms of increased geographic disaggregation, finding that this could substantially impact climate change outcomes. In a US Department of Agriculture effort, Malcolm et al. (2012) investigated the impacts of climate-related heat, drought, pests, and disease on crops. They suggested that more heat-, drought-, and pest-tolerant crops can help adaptation to climate change. In a more recent study, the model was again expanded to cover climate change effects on waterlogging and flooding, to incorporate the usage of econometric versus crop simulation-based yield projections, and to include climate change productivity projections based on econometric modeling for 18 crops and 6 categories of livestock along with the impact of surface ozone damages on crop yields (Fei et al. 2023). Analyses also indicate that climate change impacts transport infrastructure demand due to crop and livestock yield changes plus adaptation (Attavanich et al. 2013, Leclère et al. 2014). Many adaptation-related analyses have also addressed impacts along with adaptation, which is discussed in the next section.

Climate change analyses have been done on a regional basis with more emphasis on the impacts on water (Chen et al. 2005, Fei et al. 2022, Medellín-Azuara et al. 2008, Tanaka et al. 2006), and the El Niño Southern Oscillation (Chen et al. 2001, Reilly et al. 2003).

Globally, mathematical programming-based studies have shown that climate change impacts cause losses and food security issues in tropical areas, as shown by studies in Egypt, Mali, and Taiwan (Butt et al. 2005, Chang et al. 2011, Ebi et al. 2011, McCarl et al. 2015). Furthermore, in a more global modeling setting, Janssens et al. (2020) show that differing climate change impacts across regions cause food security issues and raise a need to alter international trade.

6.2. Climate Change Adaptation Studies

Many ANR global-, regional-, and farm-level climate change adaptation analyses have been done using mathematical programming, with the models incorporating adaptation alternatives. Most studies focus on shifts in crop mix, species mix shifts, management strategies, water conservation, and land use change.

Changes in crop mix are a common climate change adaptation strategy. Adams et al. (1990) found that in the United States, northward migrations of specific crops were how mathematical programming models responded to climate change. Kaiser et al. (1993) found that crop mix alteration was an effective adaptation at the farm level. More generally considering US crop production, Reilly et al. (2003) found northward and westward shifts, while Fei et al. (2017) found shifts north and west in the Midwest United States and north and east in the Pacific



Coast–bordering region, in both cases moving toward higher elevations. Choi et al. (2015) found similar adaptive shifts in Europe.

As discussed above, climate change increases the need for adaptations out of the current observation range. Adams et al. (1999) introduced crop mix shifts using an assumption that mixes could shift in from 200 miles southward and found a welfare increase, with Aisabokhae et al. (2011) showing such shifts increased production and lowered prices. Choi et al. (2015) also found that a more flexible crop mix setting (proactive reaction) can better adapt to climate change and increase welfare.

Adopting alternative crop management strategies has also been studied as an adaptation (Aisabokhae et al. 2011, Kaiser et al. 1993, Reilly et al. 2003, Thayer 2018). Possibilities include changing crop planting and harvest dates, altering the times of field operations, and switching to more heat- and drought-tolerant crop varieties. Aisabokhae et al. (2011) examined alternative possibilities and embodied those developed via crop simulation under the 2001 US National Assessment (Reilly et al. 2002). They found adaptations in the form of shifts in crop varieties, planting/harvesting timing, irrigation water usage, and crop mix provided the most valuable adaptation among a suite of possibilities. Choi et al. (2015) and Kaiser et al. (1993) also found these to be valuable adaptations.

Few ANR studies have examined livestock adaptation using mathematical programming. Weindl et al. (2015) found that livestock mix changes can be used to adapt to climate change impacts, but direct climate change effects on livestock productivity were not included. Fei et al. (2023) incorporated climate change impacts on beef cattle calving and finishing weights along with dairy cattle productivity and found adaptive north and west changes in livestock mix.

The movement of crop and livestock production also results in the need to move supporting infrastructure. Attavanich et al. (2013) found that shifting grain production location alters transport demand, reducing US barge transport and increasing rail transport. Leclère et al. (2014) found global needs for increased irrigation and shifts in processing facility locations using the mathematical programming–based Global Biosphere Management Model.

Changing agricultural land use will also be an adaptation. Globally, Leclère et al. (2014) found that by 2050, agricultural land use will be reduced in the mid- to high latitudes of the Northern Hemisphere, while more land in nonagricultural zones in North, Central, and Latin America; Australia; Turkey; the Balkan Peninsula; and Japan will be converted into cropland. Fei et al. (2022) and Thayer (2018) found shifts from irrigation to dryland and then to grazing as climate change proceeds in Texas.

Shifts in water resource use have also been examined as climate change adaptations. Leclère et al. (2014) indicates that in most of the world, irrigation needs would increase, as would the demand for irrigation infrastructure. In a regional study in South Central Texas, climate change causes less water to be used in the agricultural sector, with increased trades of water rights to other sectors (Fei et al. 2022), plus increases in deficit irrigation, and conversion of irrigated land to dryland and then pasture.

As mentioned above, climate change is a global phenomenon, resulting in nonuniform changes in agricultural production across regions and in prices. Zhang et al. (2014) found that adding climate change–induced international trade shifts into the US-centered FASOMGHG model causes significant changes in US production and export projections. Choi et al. (2015) found this shifted result in a study in Spain, as well. Butt et al. (2006) and Janssens et al. (2020, 2021) suggested that freer international trade can reduce food security issues.

Another climate change effect involves sea level rise and associated inundation/salination of cropland (Chang et al. 2011, Chen et al. 2012, McCarl et al. 2015). Chen et al. (2012) used a mathematical programming rice trade model and found that these were damaging but that developing

rice varieties that tolerate the changed climate and saltwater intrusion can reduce welfare loss, as can increased trade (Chen et al. 2012). A study in Egypt by McCarl et al. (2015) suggested that sea level protection can reduce land loss greatly and increase agricultural production and welfare.

6.3. Climate Change Mitigation Studies

The largest mathematical programming climate change literature segment involves ANR mitigation, with large efforts on bioenergy analysis and some on broader mitigation possibilities.

There have been numerous studies on bioenergy (Beach & McCarl 2010; Langholtz et al. 2016, Malcolm et al. 2009, Marshall et al. 2011, McCarl et al. 2000, Tyner et al. 1979). As biofuels have drawn much interest in climate change mitigation, many studies have focused on bioenergy and policy analysis details. De La Torre Ugarte et al. (2007) examined the consequences of a large US Department of Energy feedstock initiative. Beach & McCarl (2010) examined the effects of rules under the US Renewable Fuel Standard (RFS). Kung et al. (2013) explored using pyrolysis to replace fossil fuels and improve soil quality and carbon sequestration. Szulczyk et al. (2010) and Szulczyk & McCarl (2010) evaluated the effects of subsidies on biodiesel and bioethanol production. Beach et al. (2017) examined the impact of storage requirements and costs on biomass usage, cellulosic ethanol production, and bioelectricity generation. On bioenergy more generally, English et al. (1981), in an Iowa model, and McCarl et al. (2000), in a US model, indicated that biomass could replace significant amounts of fossil fuel in electricity generation.

The first more general study of a broad set of ANR mitigation possibilities that we are aware of was that of Adams et al. (1989). They examined changes in fertilization, livestock diets, rice planting, and tree planting. Later, a US agricultural sector model was altered to include these and other possibilities by McCarl & Schneider (2001), finding a low-carbon-price role for tillage and high price roles for afforestation and bioenergy feedstocks. Subsequently, a full-blown forest and agricultural sector model with explorations of strategy dynamics (FASOMGHG) was built by Lee et al. (2005) and then was used for a wide-ranging study over possible program design alternatives by Murray et al. (2005). Later, a voluntary carbon market, where farmers can voluntarily enroll into the carbon programs, was explored by Wang et al. (2021).

The overall ANR mitigation potential in the United States is sensitive to the incentives provided (McCarl & Schneider 2001), with low cost abatement strategies complementary to current practices used under low-carbon-price incentive levels. McCarl & Schneider (2001) also found that the capacity of emission reduction from soil carbon sequestration and non-CO₂ emission reduction was limited. At higher prices, afforestation and biofuels became the major mitigation strategies (McCarl & Schneider 2001, Schneider & McCarl 2003, Schneider et al. 2007).

Several studies have investigated livestock manure management and enteric fermentation. Frank et al. (2018) found that using more grass-cereal feeding systems for livestock can reduce non-CO₂ GHG emissions. Globally, Havlík et al. (2014) found that mitigation policy targeting land use change was more efficient than directly targeting livestock, causing less reduction in global food availability. Frank et al. (2018) included meat demand reduction as an alternative, finding that less meat will be consumed at higher carbon prices, resulting in less enteric and manure non-CO₂ GHG emissions along with less from feed production.

Several studies have found that ANR mitigation can negatively impact agricultural production. Afforestation and bioenergy feedstock production divert traditional cropland and pastureland, reduce traditional production, and increase prices (Alig et al. 1997, McCarl & Schneider 2001, Schneider & McCarl 2003). Since trees generally consume more water per acre than does cropland or pasture, Jackson et al. (2005) show that afforestation increases regional water stresses, especially in relatively arid areas. van Meijl et al. (2018) and Zhang & McCarl (2013) found that



mandating renewable fuels while achieving lower GHG emissions negatively impacts production and increases prices.

Wang et al. (2019) found that when considering bioenergy strategies, it is essential to consider the asset fixity inherent in location and feedstock use capability of existing and new facilities. In particular, they showed that ignoring asset fixity can result in unrealistic instability over time in feedstock usage patterns, costs, and locations of feedstock production.

Program design has also been examined. Wang et al. (2021) found that voluntary carbon market schemes can cause leakage and rebound effects and need baseline-related constraints to avoid such issues. Murray et al. (2005) examined issues of additionality, uncertainty, permanence, leakage, and transaction costs and showed that these can reduce mitigation efficiencies. Mosnier et al. (2013) showed that increasing mandated biofuel levels can increase the total GHG emitted globally. Findings on leakage show that unilateral policy in the European Union on beef animal-related mitigation actions can be offset by 21% to 56% by actions in the rest of the world (Frank et al. 2021, Himics et al. 2020, Pérez Domínguez et al. 2016).

6.4. Simultaneous Climate Change Impacts, Adaptation, and Mitigation Analysis

A few studies have simultaneously considered ANR adaptation and mitigation alternatives with climate change effects. Zhang & McCarl (2013) incorporated the RFS mandate with the climate change impact and examined its effects on the US agricultural sector. They found that as the RFS requires more cellulosic ethanol, crop production expands to get enough residues and lowers prices. van Meijl et al. (2018) considered mitigation under various climate change scenarios, finding that the climate change impacts on agriculture were negative and small, while mitigation with low global warming targets can have a large negative effect.

7. COMPARISON WITH OTHER APPROACHES

Simulations based on statistical/econometric equations and computable general equilibrium (CGE) models are also usable for climate change impact analysis. Here, in the context of ANR analysis, we discuss strengths and weaknesses of those techniques compared with mathematical programming models.

Simulations based on estimates statistical/econometric equations, also known as the empirical method, are commonly used to project (Reduced Form) climate change impacts. Such models have been used in two settings. The first is to identify economic impacts of climate change along with the economic consequences of adaptation strategies. For example, studies have addressed impacts on land rent (De Siano et al. 2020, Mendelsohn et al. 1994, Reinsborough 2003, Upananda & Abeysinghe 2021), alterations in cropland area and mix (Cho & McCarl 2017), livestock breed changes (Zhang et al. 2013), land use changes (Cho & McCarl 2021), and livestock species shifts (Seo & McCarl 2011, Seo & Mendelsohn 2008, Seo et al. 2010). The second setting is to estimate the physical impacts of climate change, such as crop (Chen et al. 2004, McCarl et al. 2008, Schlenker & Roberts 2009, Tack et al. 2015) or livestock yield changes (Fan 2018, Hill & Wall 2015, Yu 2014). The former application provides an alternative approach for developing economic estimates of climate impacts and adaptation benefits, while the latter is a substitute for crop and livestock simulation models in providing climate change physical impact estimates to economic models. For example, Fei et al. (2022, 2023) used the statistical/econometric models to provide information on yield and water supply effects as the input data in a mathematical programming model to evaluate ANR climate change impacts.

In general, the statistical/econometric model is a reduced-form estimation based on observed historical data. It does not require the efforts to build a structural model like a mathematical

program, CGE models, or crop and livestock simulation models, but provides a relatively accurate estimation and projection. For example, Lobell & Asseng (2017) argued that statistical models perform as well as crop simulation models in terms of estimating climate change impacts on crop yields, excepting CO₂ considerations. On the other hand, the empirical statistical/econometric models are limited by the data quality, the restriction of range, and the omitted variables. Bad data cannot yield a good estimation. A sufficient set of observations, a high-quality data set, and climate variation in excess of the range covered in the analysis are required to get good performance and well-calibrated results (Adams 1999). For example, Lobell & Asseng (2017) found statistical models perform similarly to simulation models when global warming is less than 2°C. Similarly, nonclimate conditions in the models, such as relative prices and time-independent CO₂ variations, should also be in a similar range to the conditions to be analyzed. CO₂ is highly correlated with time and is often used as a proxy for technology improvement. Independent variation is needed to identify the effect by statistical/econometric models (Attavanich & McCarl 2014, Lobell & Asseng 2017). Omitted variables issues, like the lack of treatment of soil condition, fertilizer usage, and irrigation water usage, can bias estimates, although panel model use with fixed effects can help handle that. Also, it is hard for the statistical/econometric models to unravel climate change impacts and adaptation effects (Mérel & Gammans 2021). Ricardian models have issues with the capture of future technologies, implementation of price changes, choice of the best variables to represent climate, simulation of seasonal effects, and identification of the best technique to represent the relationship between profits and climate (De Salvo et al. 2014). Nevertheless, when the data are appropriate and the issue is to project near-term change well within the range of the data, these approaches provide functions that, in all likelihood, give better projections than mathematical programs, which employ numerous assumptions and simulate decision making.

CGE models have also been used in climate change analysis (Babatunde et al. 2017, Bergman 2005, Ciarli & Savona 2019, Donaghy 2019, Hertel et al. 2009). Such models simulate market equilibrium across multiple sectors of society, endogenizing commodity prices, income, and purchasing power, and can also consider international trade. Therefore, CGE models are more complicated than partial equilibrium models that typically address one or two sectors. CGE models therefore require more data to cover the whole economy of a country, or even the whole world. The social accounting matrix is often used, as well as own-price elasticity, cross-price elasticity, and elasticity of substitution between resources, to model the substituting relationship between commodities. As a result, the data are often aggregated spatially and across commodities without much resource detail. Therefore, production and resource usage are estimated at an aggregated level. The Global Trade Analysis Project (Hertel 1999) is a commonly used CGE model for simulating both domestic production/consumption and global international trade. Limited by data availability and model size, it aggregates crops into eight categories and animals into four categories, and the United States into one region. In contrast, sectoral mathematical programming models such as the FASOMGHG model have more detailed geographic areas (63 in the United States), as do as models like Regional Environment and Agriculture Programming Model (REAP) (Malcolm et al. 2012) and Policy Analysis System Model (POLYSYS) (Dicks et al. 2009). Moreover, FASOMGHG covers over 70 primary crops and 20 livestock commodities along with more than 100 secondary food, feed and fuel products and byproducts based on the theoretical framework described by McCarl & Spreen (1980). It also covers explicit fertilization, irrigation, tillage choice, crop mix, livestock feeding, enteric fermentation management, internal transport, and other management possibilities as opposed to an often assumption-driven elasticity of substitution relationship in the CGE models (Lagomarsino 2020, Pindyck 2013).

However, CGE models can simulate impacts across sectors and interactions between income, production, and consumption, whereas partial equilibrium models cannot. This is a major



limitation of the partial equilibrium model in situations where ANR is a major source of income in a country and climate change plus accompanying policy alter that income and have a strong effect on demand. Similarly, climate change mitigation analysis where energy prices are greatly manipulated is likely best done in a CGE framework, as is commonly done in the integrated assessment community (Weyant 2017), but this approach is not without critics (Gambhir et al. 2019, Pindyck 2013).

8. FUTURE WORK

We believe climate change will be with us for many years to come, and there is a need to identify critical areas of impact, potential adaptations to pursue, and the role of ANR in mitigation. Numerous research questions in those arenas can be addressed with mathematical programming models, and we do not have the space to delve into them—a discussion is provided by McCarl & Hertel (2018). In addition, we briefly mention a couple of additional possible areas.

Many countries and regions have joined the Paris Agreement and adopted carbon-neutral goals for the near future. It is essential to find a realistic pathway to achieve these goals, such as the proper mix of wind, solar, and biomass feedstocks for bioenergy. More solar and wind farms are likely to compete with the agricultural sector in the future. Kung & McCarl (2020) included solar and wind farms in Taiwan's regional agricultural sector model and found that renewable energy can provide part of the electricity. Broader research might address this issue and ways coproduction can occur.

Most current studies only consider ANR sectors in climate change-affected resource competition and/or mitigation efforts. Involving additional sectors in the consideration of climate change-augmented resource competition for water and labor services will be important (Fei et al. 2022). It is also important to broadly cover other sectors in mitigation studies because of the leakage issue (Alig et al. 1997).

Livestock subsector analyses have been carried out in the mitigation context, as livestock are a large emitter of GHG. But less attention has been paid to livestock in adaptation analyses. Changing animal species, breeds, and management has been suggested in both adaptation and mitigation strategies by econometric and observational studies (Seo & McCarl 2011, Seo et al. 2010, Zhang et al. 2013), but no detailed investigation has been done to incorporate a wide variety of possibilities into mathematical programming models, and this area needs further research.

9. CONCLUSION

Climate change undoubtedly impacts ANR, enterprises, and markets. It is essential to estimate the climate change impacts on ANR and understand how ANR adapts to and mitigates climate. Mathematical programming has been used as an economic model to address such questions, especially since climate change moves us into previously unobserved conditions. The potential for including spatial and dynamic dimensions and the ability to add heretofore unobserved adaptation and mitigation actions provide flexibility in analyzing issues for decision making, as we reviewed in this article.

We have also covered some modeling techniques and conceptual approaches to using mathematical programming as a central economic analyzing engine. But we want to emphasize that mathematical programming does not stand on its own here, and support is needed from crop and other physical simulation models and econometric models that allow extrapolation of some physical effects, plus demand levels and intersectoral resource competition.

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