Chapter 1

Adaptation in Agriculture

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Abstract

Climate Change is continuing and happening faster than previously anticipated. Agriculture is vulnerable on a global scale and is currently adapting but will need to make further efforts in the future. Both public and private adaptation actions will need to occur, as certain potentially desirable adaptations are either not feasible or cost effective for private parties. Public action will play a crucial role in facilitating and supporting farmers to overcome barriers to adaptation and move toward a more sustainable and resilient agriculture. Here we discuss the sensitivity of agriculture to climate change and the adaptation strategies observed or potentially possible. We also discuss private and public roles in adaptation along with the constraints and barriers that limit adaptation. In addition, we discuss desirable factors to consider in adaptation project appraisal.

Keywords: climate change, agriculture, adaptation, project appraisal

1. Introduction

Climate Change (CC) is happening faster than previously anticipated and is altering agricultural conditions on a global scale. To reduce future climate risks, both mitigation and adaptation actions are likely necessary. While mitigation actions (control of greenhouse gas (GHG) emissions) reduce the future impact of CC, it takes time for such efforts to show significant effects and action has been slow to date. On the other hand, adaptation actions help reduce the negative effects of CC and can exploit opportunities [1]. Agriculture needs to adapt given the past and anticipated CC developments. Simply put agricultural adaptation is inevitable.

The evidence of that the climate is changing has grown dramatically during recent years. The IPCC mitigation report [2], shows the atmospheric concentration of GHG increased significantly with the pace increasing in recent times. According to IPCC [2], the atmospheric carbon dioxide (CO_2) concentration was 390.5 ppm in 2011, which is 40% greater than 1750 level, and exceeds 400 ppm today. Furthermore, counting other GHGs, the equivalent concentration is above 489 ppm [3]. Likewise, atmospheric nitrous oxide (N_2O) has increased by 20% since 1750 and atmospheric methane (CH_4) is 150% greater than before 1750 [2]. Greenhouse gas emissions are further projected to increase for many years. As a result, it is virtually certain that global mean surface temperatures will continue to rise. Global records show the Earth's surface temperature has been successively increasing with the three hottest observed conditions occurring in the last 3 years [4]. The numbers of cold days and nights have decreased, and we have seen increases in the number of warm days and nights and the length and frequency of heat waves [2]. Globally, precipitation has been increasing since 1901 with the spatial variability increasing and projections for large changes that differ across the planet [2].The precipitation change is not expected to be uniform with some regions projected to be drier.

All of these changes pose significant risks to agriculture. CC can affect crop yields, livestock production, water use, water supplies, and the incidence of weeds and pests among other items. CC adaptation actions are required to ensure a productive, profitable agriculture and in fact, adaptation is ongoing in the form of altered crop production locations, and planting/harvest timing along with other adaptations.

According to the IPCC [5], adaptation is the process of adjustment to actual or expected climate and its effects that in human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In addition, human adaptation actions may also occur in natural systems where actions are undertaken to facilitate "better" adjustments to the evolving climate. Such actions can benefit agriculture. For example, in a study in India, damages due to CC were predicted to be about 28 percent without taking adaptation, but 15–23% with it [6]. Moreover, in an agricultural context adaptation benefits also include reduction of income fluctuation, lessened agricultural vulnerability, and improvement in food security [5, 7–9].

A number of adaptation strategies, such as crop and livestock mix shifts, altered planting/harvesting dates, altered livestock stocking rates, and increased pesticide use, have been observed mostly implemented by farmers acting in their own best interests [10–14]. However, due to the available financial, technology, information human and physical capital not all adaptations can be privately implemented. Consequently, public parties will also play important roles in adaptation.

This paper addresses agricultural adaptation covering: (i) agricultural sensitivity and types of adaptation actions observed or projected; (ii) the roles that private and public parties play in adaptation implementation; (iii) the constraints and economic barriers that limit adaptation; and, (iv) the appraisal of adaptation projects.

2. Agriculture sensitivity and possible adaptation

CC and its drivers affect agriculture through a variety of changes, such as changes in temperature, precipitation, extreme event frequency and severity (e.g., floods, droughts, and heat waves) and increased atmospheric carbon dioxide [5]. Such factors alter crop and livestock yield, grass growth, livestock stocking rates, incidence of weeds and pests, and water usage among other items with

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geographically variability [5, 14–16]. Estimates in Beach et al. [17] show 30% projected increases in dryland corn yields in the southern US by year 2100, but little effects on the dryland corn yields in the western US and the Great Plains. Farmers have been observed to adapt on a regionally specific basis [5]. In this section, we review the nature of the effects and possible adaptations.

Finally, before starting we note that CC is not always as a negative factor but, depending on the region and situation, might also bring positive impacts to agriculture [14–20]. For example, Reilly et al. [15] presented results where moderate CC increases and the associated drivers can lead to increased cotton yield due to the effects of carbon dioxide and the drought tolerant nature of cotton. Furthermore, under such circumstances adaptation can be directed at increasing the positive aspects by say panting more of advantaged crops like cotton or increasing stocking rates for animals when grass growth is stimulated.

2.1. Crop yield

CC has been found to affect crop yield through alterations in temperature, precipitation, CO_2 level and extreme events [18, 20–23]. Lobell and Field [18] found that increasing precipitation had positive impacts on global crop yields, while the increasing monthly maximum and minimum temperature reduced yields resulting in a negative total effect. Adams et al. [21] found that yield effects vary across crops and regions in US with larger and more negative effects in the south but positive effects for some crops in the north. The Free Air CO_2 Enrichment (FACE) experimental data showed that the increase in atmospheric CO_2 concentrations increases the average yield of C3 crops (soybeans, cotton and wheat), but with little effects on the yield of C4 crops (corn and sorghum) except under drought (see the evidence reviewed in and developed by Attavanich and McCarl [20]). But Lobell and Field [18] argued that the carbon dioxide effects were minor and less than the effects of other CC factors. Moreover, Schlenker et al. [22] showed the incidence that extreme hot days (temperature over 34°C) was quite damaging to crop yields, and McCarl et al. [23] showed CC caused an increase in the variance of crop yield.

Farmers have adapted to the local climate since the beginning of farming activity. Today, they are coping with an increased pace of local CC. Crop timing changes, and crop-mix shifts are major observed adaptation strategies responding to crop yield changes. The United States Environmental Protection Agency (EPA) [12] illustrated that the average length of the US crop growing season increased by about 15 days between 1985 to 2015 with California and Arizona seasons increasing by almost 50 days. As a consequence planting dates have changed with corn and soybeans planted about 10 to 12 days earlier on average [24].

Several econometric and simulation approaches have been employed to study how farmers have been or could be adapting. Crop simulations show that adjustments to planting date and crop mix can greatly reduce the impact of CC with Aisabokhae, McCarl and Zhang [25] showing this to be the most valuable adaptation. In the U.S., the weighted centroid of major crops, such as wheat, corn and soybeans, were found to be moved to higher latitude plus a higher elevation and that the mix of crops in different locations changed [11, 23–27].

A multinomial choice model study by Seo and Mendelsohn [27] found that South American farmers in cooler locations preferred wheat and potatoes, while farmers in warmer locations planted more fruits and vegetables. They also found lower humidity pushed farmers to plant more maize and wheat [27]. Similar results were found by Park [28] using US data who found a continuum of adjustments with spring wheat dominating in cold regions, then as the climate warms corn and soybeans take over then cotton and sorghum and finally rice. Park [28] also found winter wheat and cotton were more selected in the dry locations, but soybeans were planted in the regions with more precipitation. Cho and McCarl [10] examined the impact of current and future climate on crop mixes over space in the U.S. and found that CC explained about 7–50% of the crop shift in latitude, 20–36% in longitude and 4–28% of that in elevation. Specifically, they showed that winter wheat production shifted northward and westward to cooler conditions in the Great Plains and spring wheat shifted east out of Oregon and Washington to higher altitudes and cooler temperatures in Idaho. Similarly, Fei, McCarl and Thayer [11] found the same pattern of adaptation in their modeling study. Moreover, Howden et al. [7] pointed out that CC also caused farmers to alter fertilization rates in order to maintain their crop quality.

2.2. Livestock production

CC affects livestock growth, diseases and mortality, animal reproduction rates, and quality of dairy products directly. It also has indirect effects via alterations in quality of feed crop and forage [29–31]. High temperature and humidity has been found to threaten the health, immune function, and mortality of livestock [30, 31]. Gaughan et al. [30] found elevated temperatures increased disease occurrence and mortality of new born calves plus decreased milk production. Mader et al. [29] showed that increased temperatures in hot areas decreased production of all livestock species. They also indicated that in the future the length of the feeding period would need to increase in hot southern U.S. regions, but shrink in the north [29]. Moreover, Hahn [31] showed the extreme heat waves in 1995 caused more than 4000 feedlot cattle deaths in Missouri and severe livestock performance losses in Illinois amounting to about a $28 million loss. Additionally, the number of animals dying in the heat wave in Europe 2006 and 2007 was large [30].

Livestock managers can adapt to CC through altered management, diversification of livestock varieties, alteration in livestock species and breeds, altered breeding practices, and modifying the timing of reproduction among other possibilities [7, 31–33] Hahn [31] recommended feedlot operators to use sprinklers for cooling, and to change the timing of handing and transporting particularly when the temperature humidity index (THI) is over 75. Rosenthal and Kurukulasuriya [32] provided evidence that diversification of livestock was effective in fighting against CC-related disease and pest outbreaks. Zhang, Hagerman and McCarl [33] found that summer heat stress was a significant factor for cattle breed selection in Texas with managers in regions with higher THI selecting more heat-tolerant cattle breeds (*Bos indicus*) than in other regions. A study in Africa showed that farmers changed both livestock species and mix with crops to adapt [34]. Specifically they found farmers increased reliance on livestock under hot and dry conditions, shifted to goats and sheep as opposed to cattle and chickens as temperature rose, and had more goats and chickens rather than cattle and sheep when precipitation increased [34]. Henry et al. [35] and Rowlinson [36] showed that changing breeding strategies could increase livestock tolerance to heat stress and diseases while also improving livestock reproduction. Better feeding practices, such as modification of diet composition, and changing feeding time, were found to improve the efficiency of livestock production [37].

Rosenthal et al. [32] found changing locations of livestock could help reduce soil erosion and improve moisture and nutrient retention, which in turn help adapt on the cropping side.

Herrero et al. [38] and Steinfeld et al. [39] showed that changes in crop-livestock system mix could improve efficiency by producing more food on less land using fewer resources, such as water. Mu, McCarl and Wein [13] found that increasing summer temperature plus an increased THI index caused adaptation in with the form of land switching from cropping to pasture, and stocking rates decreasing.

2.3. Water usage and supply

CC also affects agricultural water use and supply. CC alters plant evapotranspiration (ET) and thus water uptake [5]. Estimates by Adam et al. [21] show irrigated crops in the US south would need more water, but less in the north and mountain regions. Changes in precipitation, ET and crops planted have been found to affect water availability [5]. Even though the global average amount of precipitation did not show any significant changes in the recorded period (1991–2008), the observed spatial pattern and timing have changed, e.g. the frequency of heavy precipitation events increased and a downward trend of precipitation has been observed in Africa and South Asia [2, 40].

Substantial actions have been observed to adapt to water scarcity. In arid areas, where possible, irrigation and increased water storage have developed along with use of water saving technologies and drought-resilient crops [41]. Water management actions have also changed, with alterations in the amount and timing of irrigation, as have irrigation methods (with transitions from furrow to sprinkler irrigation [7, 42]). Moreover, water management strategies, such as smallholder irrigation development, rainwater harvesting, deficit irrigation and irrigation suspension are also possible as discussed in [43–47] .

2.4. Weed, pest and pathogens

CC can alter the pattern and incidence of weeds, pests and pathogens, in turn affecting crop and livestock performance and input cost [14, 47–49].

2.4.1. Weeds

Weeds compete with crops for sunlight, water, fertilizer and space, in turn reducing yields [47, 50]. CC and its drivers also affect weed growth, through temperature, precipitation, carbon dioxide concentrations, and other factors. In turn this affects the degree of competition with crops [47]. Moreover, CC is expected to shift the range of invasive weeds in turn introducing new weed issues in previously unaffected regions causing yield damages [51].

Herbicides and tillage are widely used weed control methods [49, 50]. Smith and Menalled [50] stated that integrated weed management, such as banding fertilizer near crop rows and applying it at the appropriate time, can help in adaptation, as well as can strategies such as reducing weed invasion and emergence, preventing weed reproduction, and minimizing the competition between weed and crops [50].

2.4.2. Pests and pathogens

CC affects the spread of pests affecting crops and livestock. It can enhance the spread of pests such as flies, ticks, and mosquitoes [52] plus increase disease transmission between hosts.

Mu et al. [53] found CC was associated with greater incidence of things like avian influenza. White et al. [54] found that CC led to increased Australian tick concentrations reducing animal weight by 18%. Howden et al. [7] discussed how wider use of integrated pest management can improve the effectiveness of pest control for livestock.

In terms of crops, CC induced changes in humility, precipitation and temperature have been found to alter the pattern of pathogens and their damages [49, 55]. Additionally more intense and more frequent rainfall events reduce the effectiveness of fungicides [49]. Chen and McCarl [14] showed that farmers adapted to CC induced increased pest incidence by increasing pesticide treatment costs. Wolfe et al. [49] indicated that one adaptation strategy is more frequent application of fungicides.

2.5. Climate-smart agriculture practices

Climate-Smart Agriculture (CSA) is a currently advocated adaptation approach. CSA is designed to jointly address food security and CC, enhancing CC adaptation and resilience [56]. CSA also addresses net GHG emissions. There are a number of CSA strategies and techniques that involve energy use, food storage, crop/livestock mix, water and soil management, and crop, livestock, forest, fisheries and aquaculture management [56].

3. Adaptation roles

Human adaptation through practices only occur if efforts are made to implement the practices. In many cases, farmers have been the implementers, for example altering crop rotations, changing crop mix, altering cultivars, changing the extent of tillage and revising timing of planting/harvesting. Those actions are undertaken since they are beneficial to the implementing individuals and enhance the performance of their farm business. However, some adaptation actions are so large (e.g. sea walls or research and development of climate adapted crop varieties) that farmers neither physically nor financially can individually invest in them. In addition, if they did invest in those items, those actions would benefit not only the farmer but also many others. That is, some adaptations have public-goods characteristics and following conventional economic theory will be underinvested in by private individuals [57]. This is where public action may be needed. More generally there are two forms of adaptation: (i) private (or autonomous in the literature) which is undertaken by individuals in their own best interest; (ii) public (or planned in the literature) that are adaptation actions undertaken by NGOs, or governments and designed to benefit broader elements of society (called public goods or actions to correct a market failure by economists). More details on public and private roles appear below.

CC adaptation to accommodate increases in severity or frequency of heat waves, floods, and climate related natural disasters is a great challenge. Public investments are needed to implement large and costly possibilities that benefit large segments of society or to facilitate private investment when it is limited by the state of technology, information, long-term nature of the investment or resources. Public sector adaptation efforts can take several courses: (i) they can provide incentives for private adaptation investments, such as subsidizing practices, releasing new technologies or providing low cost financing or grants [5]; (ii) they can set standards and regulations to require some degree of adaptation [58]; (iii) they can provide high-quality user-friendly information relative to adaptation needs, available strategies, and strategy implementation including technical assistance [59, 60]; (iv) they can localize information and practices to match specific regional conditions; (v) they can facilitate investment in long term adaptation capabilities (like a dam that lasts 50 years) [7, 28]; (vi) they can share in the risk and provide risk sharing mechanisms by providing insurance and possibly subsidizing it [5]; (vii) they can collaborate with the private sector in order to increase the efficiency of adaptation actions, such as carry out and providing results of R&D [61, 62]; (viii) they can identify and remove obstacles to adaptation, like distortions in input and output markets, trade barriers adverse subsidies and distorting insurance arrangements [63]; (ix) they can pursue policies that encourage adaptation investment in the context of the total development portfolio [57]; (x) they can also use policy levers like payments for environmental services; improved resource pricing; practice related subsidies, and taxes; alternative policies toward intellectual property rights; and direct actions or subsidies addressing adaptation enhancing research & technology development [5]. Studies by OECD on Innovation in Agriculture [64] and Innovation Strategy [65] provide supporting evidence that cooperation between public and private sectors improves the efficiency of public spending and induce more private firms to participate in adaptation. Those deciding on public priorities must consider whether the adaptations at hand would emerge through private actions either by farmers or supporting industries [66].

On the private side, many farmers are beginning to address climate change in their farm business planning acting in their own best interests. Farm management has incorporated climate risk into account by private parties and made changes as discussed in Section 2. In some cases, private parties can play a role in facilitating themselves into adaptation. Not surprisingly, the private sector is heavily involved in R&D of profitable crops and their products where private parties are willing to pay for the research outputs (like improved seed varieties) [66]. Private companies could also provide assistance for dissemination, creation and localization to farmers lacking information on climate change impacts and adaptation strategy type and performance [60]. Better information leads to development of private institutions to support agricultural adaptation in a variety of forms, such as better insurance, microloans, and other financial planning services. Nevertheless, there are numerous challenges when selecting appropriate adaptations. Cooperation between public and private sectors are necessary to resolve public good and market failure issues.

4. Adaptation characteristics

4.1. Adaptation constraints and economic barriers

While adaptation may be desirable, it certainly faces constraints. First, it is often constrained by available funds. Currently, on the public side there is a large gap between adaptation funding needs and actual funding. United Nations Framework Convention on Climate Change

(UNFCCC) predicted that about 28–67 billion USD funding is needed per year to adapt CC for all sectors [67]. More specifically, by year 2030 an annual estimate of global public funding needs for agriculture adaptation is about 2.3 billion U.S dollars per year [68]. However, current estimates place spending levels at around 1% of the need (FAO estimates 244 million USD for all sectors) has been provided for adaptation [69]. Moreover, adaptation is competing for funds with mitigation and non-climate investment (like education or military support or non-agricultural R&D) [5]. A balance across these three investments is required [5]. Wang and McCarl [70] find, compared to mitigation, that adaptation should get a larger investment share in the near term due to the cost inefficiency of mitigation, while when climate damage is large enough, mitigation should get more attention and investments due to increasing concentrations and damages.

Other main constraints include: (i) knowledge, and awareness, (ii) technology availability, (iii) physical and biological limits, (iv) economic and financial resources, (v) human capabilities and availability of the right types of people, (vi) social and cultural considerations, and (vii) governance and institutions [5].

There are also economic and individual behavioral barriers. These include transaction costs, information and adjustment costs, market failures, missing market, behavioral obstacles, ethics and distributional issues, coordination, government failures and uncertainty [5]. In addition, there are obstacles in the form of belief in whether CC is occurring and whether decision makers perceive needs for action.

4.2. Adaptation deficits and residual damages

Due to obstacles, belief and funding there is certainly an adaptation deficit, which is defined as "the gap between the current state of a system and a state that would minimize adverse impacts from existing climate conditions and variability" [5, 71]. Burton [71] argued and the funding gap shows that the adaptation deficit is growing. Huq et al. [72] argued this should be addressed by mainstreaming adaptation concerns in with development initiatives. It is also worthwhile noting that adaptation is unlikely to offset 100% of the damages with residual damages remaining. For example, it may be impossible to offset species extinction.

4.3. Maladaptation

Maladaptation is defined by IPCC as the case where adaptation actions lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future [5, 73]. The following two examples are considered. First, suppose a coastal city raises seawalls to eliminate the effects of sea level rise, and, in turn, the number of people and businesses located in the protected area increases. However, once future sea levels raise enough to overtop the seawall then more assets are vulnerable to CC. Second, suppose a major city with a river running through decides to divert water upstream as a flooding adaptation but the diversion results in increased flooding other places. However, despite these cases, we feel economically maladaptation should not always be prevented. Maladaptation can be rational, when overall net benefits of an action are positive and society can compensate losers [74].

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5. Adaptation project appraisal

Given the emerging presence of adaptation concerns and in place funding mechanisms there will certainly be competitive funding situations where projects will need to be appraised and their costs and benefits compared. Like in the case of mitigation there are a number of adaptation project imperfections that merit consideration. Here, we outlined the some appraisal criteria covered by adaptation funding documents and the adaptation project imperfections as below.

According to Brann [75] and the Adaptation Funding Board [76, 77], current adaptation project appraisal focuses on strategic, operational and financing priorities, country eligibility, project eligibility, resource availability, implementing institution eligibility, implementing arrangement and performance monitoring.

However, in proposed projects, imperfections may arise relative to adaptation projects in terms of additionality, maladaptation, uncertainty, permanence, transactions costs, co-benefits, and their true adaptation nature. Each is dealt with below.

5.1. Additionality

In the adaptation arena, there are two definitions of the additionality concept. In one case, the concern is that the funding for adaptation represents an increase over funding for traditional development as opposed to a redirection of existing development funds [78]. The other concern is much like that in the Kyoto arena where one asks if by funding the project are adaptation benefits achieved that are above what would have happened in the absence of adaptation funding [79]. We will only deal with the later concern here.

Ideally, adaptation funding should stimulate additional action that reduces the detrimental effects of CC or exploits CC created opportunities. This implies the needs of some form of an additionality test that checks whether the adaptation would have happened anyhow. This could use tests like those under mitigation where the activity needs to be a documented money loser or something not already implemented in the region, as mentioned by Greiner and Michaelowa [80]. However, it may be desirable to use already implemented practices if they improve adaptation in a sub-region or among select parties where they are not now used.

5.2. Maladaptation

Some adaptation actions may lead to maladaptation where they may help reduce short-run CC effects but make adaptation worse for systems in other places or the future. This indicates a need for project applications to discuss impacts on other parties within the region or affected markets. It would also be desirable to cover the effects when the project is implemented on resources and economic activity in the vulnerable region including whether: (i) more economic activities will be stimulated in a region that becomes more vulnerable as CC proceeds and (ii) the current use of resources like depletable ground water precludes future use. In addition, one should evaluate whether the maladaptation may be acceptable or the benefits of the action are substantially greater than the costs of the maladaptation to the point whether potentially gainers could compensate losers.

5.3. Uncertainty

Yet another potential imperfection involves the degree of certainty manifest in the project effectiveness measures. An uncertain future climate and a possible lack of experience with project implementation and operation yield uncertainty. It would be desirable for projects to provide say a 90% confidence interval on benefits or an evaluation of performance under different future climates as an input to evaluation.

5.4. Permanence

Permanence involves the duration of the benefits from the project and embodies the assumption that the project benefits occur over a finite life, not forever. The degree of CC is expected to grow over time and thus the effectiveness of a given amount of adaptation expenditures is expected to fall as CC proceeds [81]. Therefore, it may be desirable for proposals to discuss activity life and its performance under escalating degrees of CC.

5.5. Transactions costs

Implementing and monitoring projects involves costs of passing funds to producers, insuring results, and observing/monitoring progress. Project applications might well cover the means for conveying funds, any brokerage fees involved and the methods/cost of insure the project operates as it is supposed to.

5.6. Co-benefits

Many possible adaptations have multidimensional implications including for example contributing to CC mitigation, improving current food security and correcting adaptation deficits. As such, project funders need to decide whether to evaluate or neglect such outcomes and the extent to which the funds flow into generating those co-benefits or to true adaptation. Project applications should layout not only adaptation benefits, but rather the entire spectrum [82, 83]. Nevertheless, evaluators must be cautioned as full consideration of co-benefits imposes a large burden in terms of identifying and quantifying co-benefits for all the projects at hand not just selected ones. In turn, evaluators will need to develop an approach to valuing the non-adaptation benefits and expenditures associated with the non- adaptation items stimulated by the project. However, Elbakidze and McCarl [84] argued that when appraising mitigation programs, the co-benefits should perhaps be neglected because co-benefits raises more uncertainties and burden to evaluate and qualify them across all projects, which should be considered here as well.

5.7. Is it really adaptation

The final issue is one of where the proposed activity is really adaptation. Lobell [19] argued that many suggested "adaptations" did not effectively reduce vulnerability under a changing climate. He argues that the benefits of adaptation actions should rise with degree of CC but that most of the ones cited in IPCC documents do not achieve this. Moore et al. [85] did a meta-analysis on the issue and found that virtually all the agriculturally related adaptation benefits reviewed by IPCC in the latest assessment report yield benefits that are independent of the changes in temperature or precipitation. This means such strategies while likely beneficial do not improve adaptation to CC.

6. Conclusion

Coping with a changing climate is an increasingly important issue in agriculture and one that is likely to persist for many years. In order to improve performance, farmers will need to adapt. Some adaptation efforts will happen in association with farmers making the best management decisions for their operation. But a class of possible adaptations can (i) face barriers being too costly for individual implantation, (ii) be hindered by substantial resource limits or behavioral barriers that the individual cannot overcome or (iii) yield benefits that spread widely across society and are not captured by an implementing individual. In such cases, public-sector intervention may play a crucial role in actual implementation or in the facilitation of producer adaptation implementation. Lastly, in comparative assessment of adaptation actions, one must also collect and evaluate information not only on benefits and costs of proposed adaptations but also on their imperfections in terms of additionality, maladaptation, uncertainty, permanence, transactions costs, co-benefits and true adaptation effectiveness.

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