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UNRAVELING COMPLEXITY: EXPLORING AGRICULTURAL SYSTEMS AS COMPLEX ADAPTIVE SYSTEMS WITH A FOCUS ON THE KONYA CLOSED BASIN

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Abstract: The study of complex adaptive systems (CAS) has garnered significant attention across interdisciplinary research, particularly within the realms of social and natural sciences. This paper delves into the multifaceted nature of CAS, exploring its definitions, components, and properties, drawing from various scholarly perspectives. It examines the agricultural sector as a prime example of a CAS, highlighting the interactions, adaptations, and emergent behaviors within farming communities. Using the Konya Closed Basin in Türkiye as a case study, the paper elucidates how agricultural landscapes exemplify the complexities inherent in CAS, underscoring the intricate interplay between human activities, environmental dynamics, and socio-economic factors. By recognizing these interactions, decision-makers can create more efficient and resilient strategies for managing water resources, enhancing crop production, and reducing the effects of climate variability. This comprehensive approach emphasizes the role of adaptation, self-organization, and emergent behaviors in promoting sustainable farming practices and maintaining ecological balance over the long term. Through this analysis, the paper contributes to a deeper understanding of CAS and its implications for sustainable agricultural development and resource management.

Keywords: Complex adaptive systems, Agriculture, Konya closed basin

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1. Introduction

The study of complex adaptive systems, which are a type of non-linear dynamic systems, has become a significant focus of interdisciplinary research across social and natural sciences. The field of Complex Adaptive Systems (CAS) was founded by economists, physicists, and other researchers investigating complexity at the Santa Fe Institute in the early 1980s. CAS represents both a field of study and a conceptual framework for understanding natural and artificial systems that resist reductionist (top-down) analysis (Waldrop, 1992).

Much of our scientific understanding of nature has been achieved through the process of reducing complex phenomena at higher levels to simpler ones at lower levels. While scientific reductionism has proven highly successful in explaining chemical phenomena at the molecular level using the atomic model from physics, its application in the life and social sciences has been more limited. Addressing profound questions in these fields has necessitated multidisciplinary research, drawing from diverse fields such as biology, physics, computer science, and economics. This interdisciplinary approach has given rise to a new field of study known as Complex Adaptive Systems. These systems are typically characterized by populations of adaptive agents whose interactions give rise to complex, non-linear dynamics, resulting in emergent system phenomena.

Some examples of CAS could be the immune system, genetic evolution, market economies, cultures, flocking of birds, brain, and evolution of languages (Chowdhury, 1999; Markose, 2005; Rammel et al., 2007; Ellis, 2009; Rogers, 2017; Carmichael and Hadzikanic, 2019). These examples are drawn from a wide range of disciplines such as biology, economy, sociology as the discipline of complexity itself is holistic and highly interdisciplinary (Holland, 1992; Gell-Mann, 1994; Lansing, 2003; Levin et al., 2003; Buckley, 2017).

Agricultural systems can also be given as an example for complex adaptive systems (Berger, 2001; Gallopin et al., 2001; Janssen et al., 2007). This paper uses a case study approach to exemplify the attributes and properties of a complex adaptive system. Therefore Konya Closed Basin is chosen as a representative agricultural setting where a number of challenges such as climate variability, over-extraction of groundwater, soil degradation, sinkhole formation, habitat destruction exist (Demir, 2022; Todaro et al., 2022; Yoloğlu et al., 2023). These socio-environmental challenges make CAS as a relevant framework to better understand and act upon these issues.

This paper aims to provide various definitions of Complex Adaptive Systems and to describe their components and properties (Section 2). Section 3 elucidates why agricultural systems can be considered Complex Adaptive Systems. In Section 4, a case study of an agricultural system in the Konya Closed Basin, Türkiye, illustrates how it can be viewed as a Complex Adaptive System. The Conclusion section summarizes the findings and implications of the study.

2. Definition of Complex Adaptive Systems

Complex adaptive systems (CAS) are ubiquitous and underpin both the intricate challenges and rewarding endeavors within society. Inherently captivating, CAS exhibit distinct characteristics such as profound complexity, resilience, and a proclivity for innovation. Despite extensive scholarly exploration, a unified definition of CAS remains elusive, with scholars offering sets of parsimonious principles and properties (Levin, 1998; Gallopin et al., 2001; Mitchell, 2006; Siegenfeld and Bar-Yam, 2020). This conceptual elusiveness persists at both qualitative and quantitative levels. Moreover, the multidisciplinary nature of CAS research contributes to the absence of consensus, as each discipline brings its specialized characteristics to the definition. Similarly, the absence of a standardized quantitative measure of complexity further complicates matters (Axelrod and Cohen, 1999). The very factors that complicate the nominal definition of CAS also render the field attractive to diverse disciplines, as the concept of complexity finds applicability across various domains, with its approach adapting to the specific discipline. However, amidst this diversity, recurring themes of agents and interactions persist. Despite the absence of a shared definition, these systems share a common underlying structure.

Schuster (2001) defines complex adaptive systems as networks composed of elements such as neurons, genes or agents in a game, which interact non-linearly with one another and with their environment. These elements gather information from their surroundings and convert this knowledge into actions that provide specific advantages (Schuster, 2001). Plsek and Greenhalgh (2001) define a complex adaptive system as a collective of individual agents endowed with the freedom to act in unpredictable ways, with their actions interconnected such that one agent's behavior can alter the context for others. Examples range from the immune system and colonies of termites to financial markets and diverse human collectives such as primary healthcare teams. Mitchell (2009) describes complex systems as extensive networks of interconnected components that operate without central control. These systems follow simple operational rules, leading to intricate collective behaviors, advanced information processing, and adaptation through learning or evolutionary processes.

With the accumulation of knowledge in each discipline, we have entered a new era in our capacity to comprehend and advance complex systems. These systems continuously change and reorganize their components to adapt to the challenges posed by their environment. This adaptability is the primary reason these systems are difficult to understand and control. Another difficulty may be distinguishing the systems as complex or not and giving the answer to the question: What makes systems complex? The distinction between simple and complex systems may look very straightforward; however, it is not (Gell-Mann, 1994; Mitchell, 2009). At the same time, a system that appears to be very complex can be explained very simply. Scale of definition is an important parameter in defining the systems as complex or simple. The definition of complexity is not trivial, and different conceptions exist, but one point to emphasize is that complexity is not an automatic outcome of increasing the number of elements and/or relations in a system. Complex systems generally exhibit a number of attributes that make them more difficult to understand and manage than simple and complicated systems. Complex systems have common characteristics and many authors have listed the properties and components that make the systems complex and adaptive. Synthesizing the literature reveals five attributes of systems that qualify them as complex adaptive systems: i) interconnectedness of elements, ii) learning and adaptation, iii) dynamic nature, iv) self-organization and emergence, v) resilience.

2.1. Interconnectedness of Elements

Complex adaptive systems are composed of diverse, interconnected elements, making it difficult to determine the boundaries of a given system. As Cilliers (1998) emphasizes, CAS are treated as open systems, meaning that external elements and systems can affect the behavior of the system. This implies that the system exchanges energy, information and matter with its environment (Preiser et al., 2018). Furthermore, lagged response to any intervention in such interconnected systems makes it harder to comprehend system structure and estimate its behavior (Saito et al., 2021). This property complicates the task of defining system boundaries, making them more dependent on how the system is described and the perspective of the observer.

2.2. Learning and Adaptation

According to Holland (1995), as time goes on, the parts that make up the complex system evolve in Darwinian fashion, attempting to improve the ability of their kind to survive in their interactions with the surrounding parts. This ability of the parts to adapt or learn is the pivotal characteristic of complex adaptive systems (Holland, 1992). Although some adaptive systems can be very simple, in the study of CAS, interest is focused on systems that constitute of numerous interactive parts or agents.

In seeking to adapt to changing circumstances, the parts can be thought of as developing rules that anticipate the consequences of certain responses (Holland, 1992). For example, anticipation of an oil shortage can complicate the economic system’s behavior through price increase and an accelerated search for alternative energy sources.

This example demonstrates the influence of anticipation in complex system behavior. In other words, anticipation hints at adaptiveness of a system. Complex adaptive systems form and use internal models to anticipate the future, basing current actions on expected outcomes (Holland, 1992). Due to continuous adaptation of the system, new opportunities for exploration are created and the result is ongoing perpetual novelty (Arthur, 1997). Yet one has to keep in mind that complex adaptive systems are not necessarily adapting to every situation or to every change.

2.3. Dynamic Nature

According to Holland (1992) and Kelly (1994) complex systems never reach the optimal point that economics or physics usually aim to reach. Once the systems are in equilibrium they are considered to be "dead" or they are not interesting enough to be studied anymore. The appealing property of complex adaptive systems is the path that they follow trying to reach the optimal point, rather than the optimal point itself (Waldrop, 1992).

According to Cilliers (1998), large numbers of elements interact in a dynamic way with much exchange of information and these interactions are rich, non-linear, and have a limited range because of the lack of over-arching framework that controls the flow of information. The non-linearity in the system might lead to disproportionately large effects and the system's state can shift in abrupt and unpredictable ways (Walker, 1998). Non-linearity often involves feedback loops, where the output of a process feeds back into the system as an input, influencing subsequent behavior. These feedback loops can be either positive or negative. Positive feedback loops amplify changes within the system, leading to exponential growth or runaway effects, whereas negative feedback loops act as a self-regulation mechanism, dampening or mitigating fluctuations and promoting stability. The non-linear feedback relationships within complex systems are challenging for the human mind to comprehend (Lock, 2023).

Non-linear dynamics may also involve threshold effects, where a small change in the system may trigger abrupt transitions or may even lead to phase transitions, however challenging to predict (Lenton, 2013). Thresholds are often associated with tipping points (Folke, 2006), where a system might go through irreversible changes.

2.4. Self-organization and Emergence

Holland (1992) states that complex adaptive systems exhibit an aggregate behavior that cannot simply be derived from the actions of the parts. He uses the character of aggregate behavior to hint at the concept of emergence. Patterns emerge from the dynamic and non-linear interactions between the systems, and between the low-level adaptive agents. The emergent patterns are more than the sum of the parts, thus the traditional reductionist methodology fails to describe how these patterns emerge.

At the core of CAS theory is the idea that global complexity is not imposed from above but rather *emerges* from the interaction of agents that are following simple local rules, an example of self-organization. A system is called self-organizing if the individual parts of the system interact in such a way that certain structures and possibly complex structures arise without external influence (Kauffman, 1995; Mitchell, 2009). Hence, new patterns, structures, or behaviors emerge from the interactions between the system's component and they are not predictable based solely on the characteristics of individual component but arise from the collective behavior of the system (Mitchell, 2006). These rules are local in that they are applied by each individual agent rather by the system as a whole. Flocking of birds with a couple of rules can be a good example of emergence and self-organization (Kauffman, 1995).

2.5. Resilience

Typically, discussions on resilience are presently grounded in the framework of a social-ecological system (SES), depicting an interplay between a society's cultural and institutional structures and its physical surroundings (Gunderson and Holling, 2002). Social ecological systems are considered as complex adaptive systems and they are organized around continuous change and adaptation (Hartvigsen et al., 1998; Levin, 1998; Berkes et al., 2003). The concept of a social-ecological system (SES) is conceived as an interplay between a society's cultural and institutional structures and its physical environment. Significantly, a society relies on the physical environment, transforming it into practical resources like food, raw materials, and energy. The cultural and institutional arrangements go beyond merely mediating human interactions; they also determine the degree of efficiency in utilizing the environment. Consequently, many authors view society and nature as interconnected, considering the distinction between natural systems (biophysical processes) and social systems (rules, norms, institutions, and knowledge processes) largely arbitrary (Berkes and Folke, 1998; Carpenter et al., 2001; Berkes et al., 2003; Folke, 2006; Ostrom, 2008). Components of this change are the processes of increasing connections across several scales and the locking up of resources that then cause the system to become susceptible to a collapse initiated by a minor disturbance (Gunderson and Holling, 2002).

Resilience in the context of CAS and social-ecological systems refer to the capacity that a system can absorb disturbances, adapt to changing conditions while retaining the core functions, structures and feedbacks (Holling, 1973; Peterson et al., 1998; Gunderson & Holling, 2002; Walker et al., 2004). Resilience of a system also hints at the capacity to self-organize and the degree to which the system can maintain learning and adaptation (Carpenter et al., 2001). Incorporating resilience thinking to resource management could better prepare decisions and policy makers to better prepare for uncertainties and changes that are intrinsic properties of complex adaptive systems (Folke et al., 2010).

To summarize, complex systems are typically organizations made of many heterogeneous parts interacting locally in the absence of a centralized control. Most definitions of complex adaptive systems include emergent properties, self-organization, and non-linearity. These properties will result from the absence of a global controller, constant adaptation and learning. Constant adaptation implies continuous change, thus dynamics are typically far from equilibrium where non-linear dynamics are frequently exhibited. The high potential for emergent properties in complex systems arises from interactions of many independent units at local scales. Complex systems are often self-organizing, thus complex higher-level patterns can emerge from the behavior of independent units that follow simple behavioral rules. Complex behavior arises from the interactions between system components (or agents) and their environment. By engaging with and learning from the environment, a complex adaptive system adjusts its behavior to respond to environmental changes.

3. Agricultural Systems as Complex Adaptive Systems

Agricultural systems are composed of various different components that take part in the production of food and goods through farming and forestry. There are many models and simulations of agricultural systems that do not explicitly use the framework of CAS, although they do utilize some of the computational tools (such as agent-based models), and terminology (emergence, agents, etc.) (Berger, 2001; Gallopin et al., 2001; Happe et al., 2006; Rammel et al., 2007; Foran et al., 2014; Chapman et al., 2017; Preiser et al., 2018; Jagustovic et al., 2019). Agricultural systems qualify as complex systems as they consist of interconnected groups of resource users linked to various resources, all governed by institutions at multiple scales. Such multilevel and multi-scale systems present significant challenges study and comprehension (Janssen et al., 2007).

Interconnectedness is a fundamental property of complex adaptive systems (CAS), characterized by the dynamic interactions among diverse elements within the system (Preiser et al., 2018). In agricultural systems, this interconnectedness is evident through the intricate relationships between crops, soil, water, climate, pests, and human activities. For instance, the health of the soil affects crop productivity, which in turn influences the types of pests and diseases that may proliferate. Farmers' decisions on crop rotation, irrigation, and pest control create feedback loops that impact not only their own fields but also neighboring farms and the broader ecosystem. Additionally, external factors such as climate change introduce new variables, altering these interactions in unpredictable ways (IPCC, 2022). For example, changing rainfall patterns can affect soil moisture levels, leading to shifts in crop viability and pest populations. This interconnected web of relationships illustrates how the behavior and outcomes emerge from the complex interactions among various numerous elements rather than from any single component alone. In addition, high level of interconnectedness inevitably increases the complexity and uncertainty within agricultural systems, through rich non-linear feedback.

Agricultural systems face both predictable and unexpected spatial and temporal variations of social and natural variables. Adaptation acts as a core property of complex adaptive systems and agricultural systems demonstrate this property in numerous ways (Arthur, 1997). In agricultural systems, one of the most important natural variables can be temperature and precipitation and social variables can be population structure, policy and commodity price. As a complex adaptive system, agricultural systems have the ability to adapt, however to some extent. As Holland (1992) lists anticipation as one of the properties of CAS, farmers as agents in agricultural systems anticipate these fluctuations and take preventive actions to minimize the impacts of these fluctuations; in other words, they are trying to increase their resilience to these fluctuations or external shocks. For example, under changing climatic patterns, farmers modify their crop patterns (i.e., choosing drought resistant crop species), alter their harvesting and planting dates, employ advanced irrigation technology to conserve water or may even consider abandoning the profession, which all can be considered as adaptation strategies. From the socio-economic perspective, farmers adapt to changing crop prices, agricultural policies, and changing demographic realities. Nevertheless, having the ability to adapt does not mean that these systems are robust to any change; hence, the agricultural systems can be considered as robust yet vulnerable to infrequent, unexpected, but possibly devastating fluctuations.

Another common observation among the scholars of complexity science is the analogy of equilibrium to death, as complex adaptive systems are particularly studied for their dynamic properties. Agricultural systems demonstrate the non-linearity and dynamic nature through their intricate feedback loops and sensitivity to factors within the agricultural system. For example, cropping systems are very sensitive to temperature changes and a slight increase in temperature might lead to pest outbreaks, impact crop yields, and reduce soil moisture levels, resulting in cascading impacts in the entire system. Similarly, minor changes in water availability can disproportionately affect crop yields due to the non-linear relationship between water supply and plant growth (Kumari et al., 2022). Crops often have critical thresholds for water needs; once water levels drop below these thresholds, even slightly, plant stress increases rapidly, reducing growth and productivity. This non-linearity means that a small decrease in water availability during key growth stages, such as flowering or fruit development, can result in substantial yield losses, as the plant's ability to recover diminishes once critical moisture levels are breached. Additionally, introduction of a new crop variety or farming technique might alter the crop dynamics, pest management and can lead to unexpected interactions further exemplifying the system's dynamic and non-linear nature.

Farmers within an agricultural context are not independent from each other. Through various institutions such as markets for land, conservation practices and shared resources, there are strong interactions and dependencies between farmers. As an example, farm sizes depend on their neighbors. Farmers can increase their area if other farms shrink in size or close down. Similarly, the prices that farmers face are influenced by the market, which is determined by the aggregate output of all the farmers, demonstrating another link between individual farmers.

In agricultural systems, self-organization and emergence are evident in practices such as crop rotation, which arise from farmer's intrinsic knowledge rather that top-down initiatives dictated on farmers. For example, farmers may observe that rotating crop increase soil health and reduce pest infestations, which might lead to the spread of knowledge through farmer networks and result in widespread adoption of a practice based on localized experience. From another dimension, the collective behavior of pollinators and pests can exemplify the self-organized behaviors and emergent properties.

Agricultural systems can be considered as Social Ecological Systems where the changes occurring in the physical systems such as reduction in water supply will drastically impact the farmers decisions hence impact the social system. In accordance, with the reduction in water availability, farmers would inevitably change their strategies and be inclined towards adopting water efficiency strategies or change their crop types, consequently reducing their water needs. For agricultural systems, resilience is a crucial property for ensuring food security, sustainable livelihoods and ecological balance. Resilience refers to the system being able to retain its core functions while absorbing the shocks and adapting to changing conditions (Folke et al., 2010). Agricultural systems face numerous shocks and disturbances such as extreme weather events, pest infestations, market fluctuations, and changes in policy. Ideally a resilient agricultural system would absorb these shocks and disturbances without losing its operative functions. The perspective of 'robust, yet fragile' contends that systems develop intricacies that render them remarkably resilient to uncertainties in both the environment and system components. Consequently, they become highly susceptible to rare and unforeseen disturbances (de Goede et al., 2013), bringing the concept of achieving resilience to the center of management targets.

Heavily managed systems, such as agricultural systems, are fragile and vulnerable to possible single stresses such as pest outbreaks that may cause system crashes in the absence of adaptive responses (Carlson and Doyle, 2002). Thus, if resilience is a goal, managers must understand the properties that enable an ecosystem, as a complex adaptive system, to maintain its integrity in the face of changing environmental conditions and human impacts.

4. Konya Closed Basin as an example of Complex Adaptive Systems

4.1. Background on Konya Closed Basin

The Konya Closed Basin (KCB) is situated in Central Anatolia, Türkiye, covering an expansive area exceeding 62,000 km^2 (Figure 1). It stands out as one of the 25 watersheds in Türkiye. Renowned for its substantial agricultural potential, the basin has historically served as the primary wheat production center of the country. Consequently, the local population boasts a rich agricultural heritage, with industrial production intricately linked to agricultural activities. In recent times, both industrial and agricultural outputs have witnessed a surge, contributing to an expansion of the region's role in the national economy and trade. Simultaneously, the basin represents an ecological hotspot, hosting a plethora of endangered plant and mammal species. Furthermore, it serves as a crucial breeding ground for numerous endangered bird species (WWF, 2014).

Agriculture overwhelmingly dominates the utilization of water and land resources in the basin. Approximately 78% of the total water consumption, including both surface and groundwater, is allocated for agricultural purposes. In 2018, the Ministry of Agriculture and Forestry estimated that up to 90% of water resources, comprising both surface water and groundwater, were utilized for irrigation (T.C. Tarım ve Orman Bakanlığı Su Yönetimi Genel Müdürlüğü, 2018). Drinking and utility water consumption follows, accounting for approximately 8% of the overall water use.

The industrial sector stands as the third-largest consumer of water in the basin. Key industries driving water demand in the region include the production of fabricated metal products, food items, furniture, rubber and plastic products, garments, motor vehicles, wood products, non-metallic mineral products, as well as leather and related products.

The basin is known as the granary basket of the country, as the precipitation patterns match with the water needs of grains. The basin mostly receives precipitation during the winter months and nearly none during the dry summer season. The average annual precipitation in the basin is 300-350 mm, nearly half of the average annual precipitation in Türkiye (740 mm). Evaluating historical meteorological data reveals an upward trend in temperature in the basin, leading to hotter and longer summers. Winters, on the other hand, have seen fluctuations with precipitation being mostly in the form of rain (Figure 2). Todaro et al. (2022) analyzed precipitation and temperature trends in the Konya

Closed Basin until the end of the century for two representative concentration pathway scenarios (RCP 4.5 and RCP8.5) using an ensemble of 17 Regional Climate Models. This analysis reveals that in the future the basin will experience higher temperatures, with similar precipitation patterns (Figure 3).

Summer crops or greens crops (sugar beet, corn, potato, sunflower, etc.) as referred by locals have much higher irrigation demand compared to grains that are grown during the winter season. With the introduction of sugar beets in 1960s, the irrigation needs of the crops increased and farmers started drilling wells for groundwater access. Increased production of sugar beets was followed by development of food and beverage industry dependent on sugar beets, leading to an irreversible lock-in to the crop choice. The economic development brought by the sugar beet plantations was followed by the switch to corn production. In early 2000s, the production of green crops such as corn, sunflower and potato started to increase, with the switch from rain-fed agriculture to irrigated agriculture, the irrigation water demand increased (Figure 4). Currently, corn is a favorable crop choice in the basin due to its profitability and low maintenance.

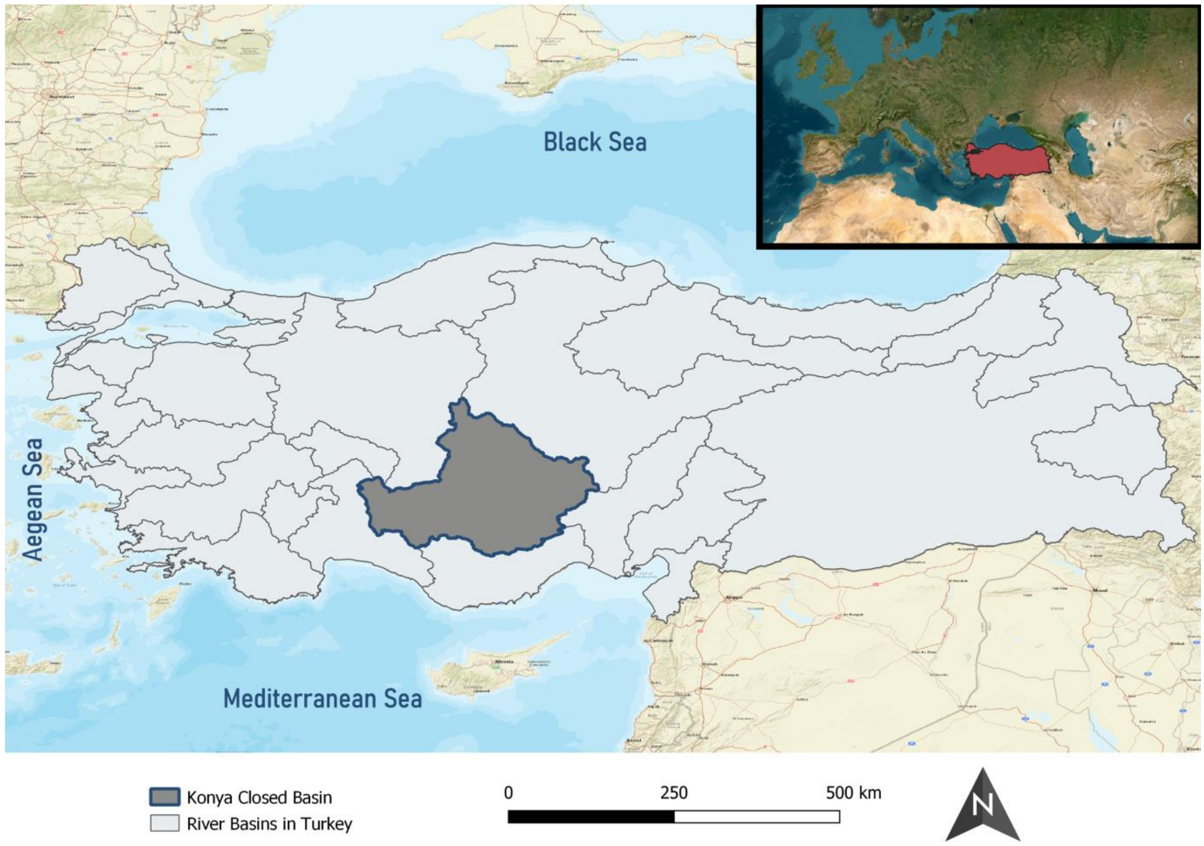

Figure 1. Location of Konya closed basin, Türkiye.

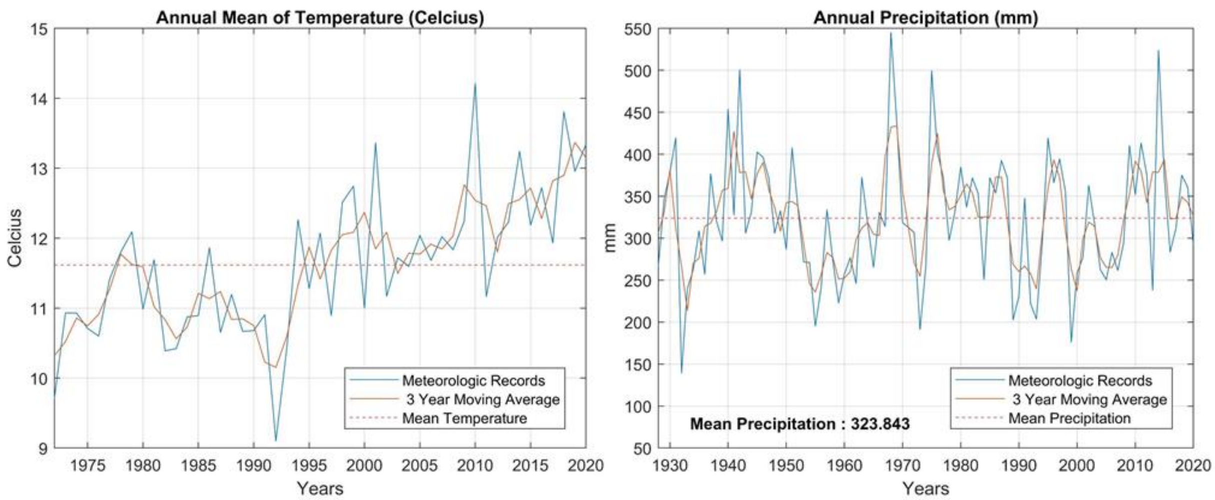

Figure 2. Change in historical (1975-2020) mean temperature and precipitation in Konya Closed Basin.

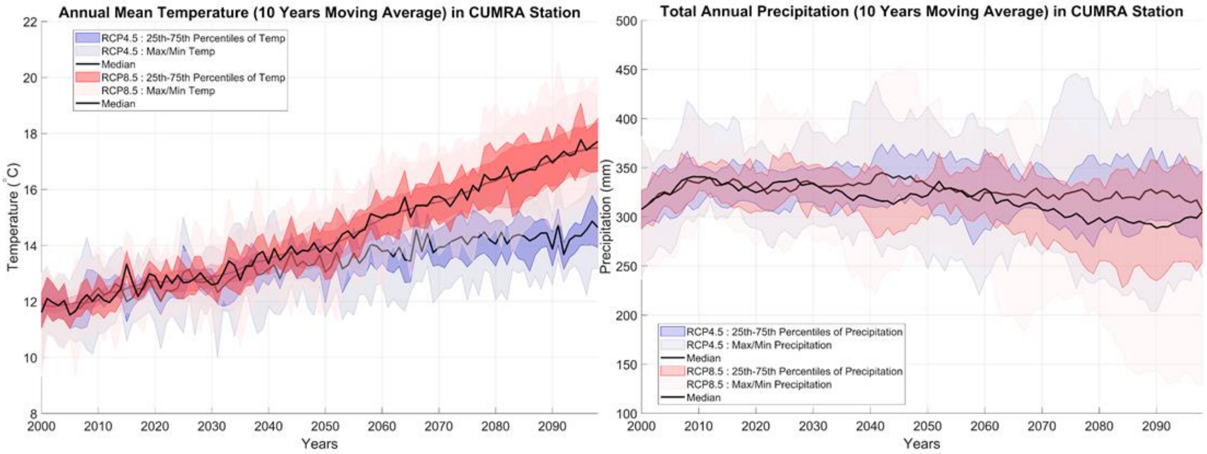

Figure 3. Change in temperature and precipitation in future (2020-2099) in Konya Closed Basin with 10 year moving average projected by the 17 RCMs for RCP 4.5 and RCP 8.5 (Todaro et al., 2022).

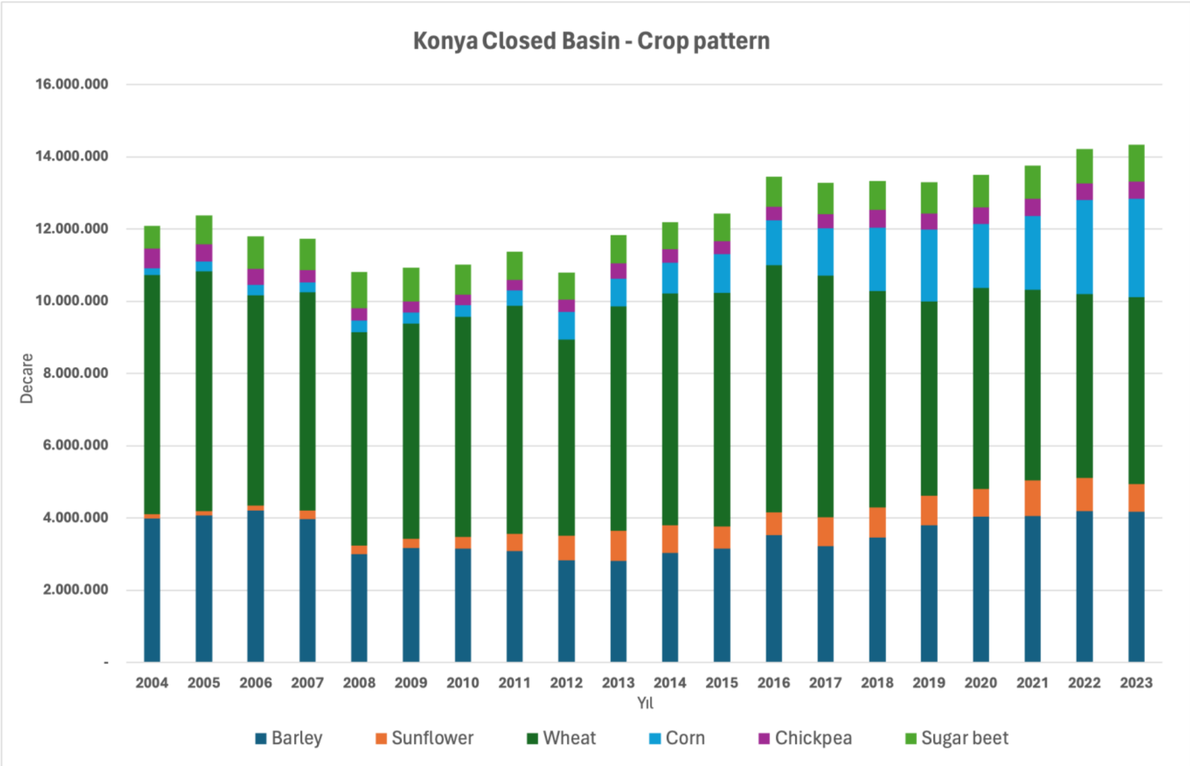

Figure 4. Change in crop patterns in Konya Closed Basin (TÜİK, 2024).

The switch towards high water demanding green crops resulted in a decrease in the groundwater table in the basin. Since 1980s, the groundwater table – main water resource in the basin- is decreasing (Yoloğlu et al, 2023). When farmers initially started using groundwater for irrigation, they were using low power pumps, even in some cases hand-dug wells, but currently in some regions such as Karapınar, the groundwater level is rapidly decreasing, leading to sinkhole formation (Göçmez et al., 2022).

Before the introduction of green crops, farmers were reliant on precipitation and did not utilize irrigation methods. However, when sugar beets were introduced to the basin, farmers dominantly used flood irrigation and as groundwater levels were decreasing, modern irrigation methods were slowly introduced to the basin. Since 2000s, government incentives increased the adoption of modern irrigation technology in the basin and currently drip and sprinkler irrigation methods are dominantly used for corn and sugar beet production.

4.2. Konya Closed Basin as an Example of Complex Adaptive Systems

The Konya Closed Basin acts as a good example of complex adaptive systems due to several factors. The basin's socio-economic well-being stands on the ecological elements of the basin such as water and soil quantity and quality. These components interact dynamically, influencing each other's behavior and contributing to the overall system dynamics. The sustainability of the basin depends on the valuable natural resources such as water, soil, and biodiversity. These resources are interconnected through ecological processes, with water availability influencing soil quality, vegetation distribution, and habitat suitability for wildlife. The intense agricultural activity within the basin are tightly linked to industrialization and therefore to natural resource utilization and management. The agricultural production increasingly being dependent on groundwater irrigation and increased agricultural production fueling the industry and labor markets dependent on agricultural production. The economic activities within the basin such as agricultural production trade, services are interconnected through supply chains, market dynamics and financial transactions. Any possible change in one sector can have ripple effects across the entire economics system. The KCB has food and beverage manufacturing industry dependent on the sugar beet production in the basin. Any change in the production levels of the sugar beets can potentially have an impact on the employment and income distribution. Overall, the interconnected components within the Konya Closed Basin form a complex web of relationships and dependencies, where changes in one aspect of the system can propagate through multiple pathways, affecting the resilience, sustainability, and adaptability of the entire basin.

As water scarcity in the region becomes increasingly severe and the impacts of climate change more pronounced, alongside alarming land degradation, the implementation of adaptation strategies has become essential. In response to more frequent droughts in recent years, farmers are increasingly shifting towards drought-resistant and less water-intensive crops, such as sunflowers (Ataseven et al., 2022; Gürkan, 2019). Additionally, the Ministry of Agriculture and Forestry has introduced incentives to promote water efficiency, particularly targeting 11 provinces and 52 districts facing water scarcity, of which the Konya Closed Basin comprises 31 (Ministry of Agriculture and Forestry, 2023). Efforts across the basin, especially in water-stressed areas, have been focused on encouraging the adoption of water-saving technologies like drip and sprinkler irrigation (Kaya, 2017).

The interactions within the basin exhibit non-linear dynamics, meaning that small changes in one component can lead to significant, often unpredictable, effects on the entire system. A small increase in water availability due to rainfall may lead to a disproportionately large increase in agricultural productivity, but only up to a certain threshold where further increases in water availability may have diminishing returns or even negative effects due to waterlogging or soil erosion (Kumari et al., 2022). Such phenomena is observed in KCB when farmers switched from rain-fed irrigation to flood irrigation in early 1990s. Initially crop growth solely depended on rainfall patterns, this traditional farming method was well-suited to the arid and semi-arid climate of the region, but it produced low yields due to the limited water supply and unpredictable rainfall patterns. The reliance on groundwater and consequently drilling of groundwater well across the basin, lead to a significant shift from rain-fed farming to irrigated agriculture. This change was seen as a solution to food security and economic development in the region, encouraging farmers to grow water-intensive crops such as sugar beets and corn, which offered higher economic returns. When groundwater was introduced as supplementary irrigation, crop yields initially increased. However, the use of low-efficiency methods like flood irrigation did not sustain this growth. Instead, inefficient irrigation practices, particularly flood irrigation, have contributed to the salinization of soils. This process occurs due to the excessive application of water in a region with high evaporation rates, leaving behind salts as the water evaporates. Salinized soils, in turn, reduce crop productivity and further degrade agricultural land (Tunca et al., 2023). Moreover, the combined pressures of intensive farming and inefficient irrigation have depleted soil nutrients over time, diminishing soil fertility. The widespread use of chemical fertilizers and pesticides has exacerbated this degradation, further compromising soil quality.

Furthermore, with intensive irrigated agriculture, the demand for groundwater has escalated leading to significant drops in groundwater level (Yoloğlu et al., 2023) and formation of sinkholes (Demir, 2022; Orhan et al., 2024). Conversion of previously grazing land to irrigated crop production also disrupts natural habitats, leading to a decline in biodiversity (Uzun et al., 2011; Yılmaz et al., 2021). Native plant species and wildlife that depend on open grasslands are displaced or endangered as agricultural monocultures expand.

Non-linear dynamics often involve feedback loops. In KCB, intensive agriculture, particularly water-intensive crops like sugar beets, demands large quantities of water. This results in over-extraction of groundwater, causing aquifer depletion. As water levels drop, farmers have to dig deeper wells, increasing both the cost of water extraction and the energy required to pump water, which amplifies economic strain on farming communities. This positive feedback loop resulted in higher numbers of wells in the basin. Intensive farming practices often involve overuse of chemical fertilizers and monocropping, which degrade soil health. As soils become less fertile, farmers rely more on external inputs, creating a vicious cycle of diminishing returns—higher input costs but lower yields over time. Continuous land use without sustainable management leads to desertification in the basin, reducing the land's productivity and its ability to retain water. This forces farmers to intensify extraction from already scarce water sources, perpetuating a feedback loop of water scarcity and land degradation. On the contrary, negative feedback loops, act to stabilize the system by counteracting changes. For example, groundwater levels decrease due to extraction for irrigation, the cost of extraction increases (water needs to be pumped from greater depths) requiring more energy and higher operational costs. The higher extraction costs could lead to reduced groundwater usage as farmers aim to minimize their expenses. Non-linear dynamics may also involve threshold effects. In the KCB, for instance prolonged droughts or over-extraction of groundwater may push the system past critical thresholds, leading to shifts in ecosystem dynamics, water availability, and socio-economic conditions.

Within the basin, the spatial distribution of agricultural activities, including crop cultivation, livestock grazing, and irrigation infrastructure, often exhibits self-organizing patterns. These patterns emerge from the decentralized decisions and interactions of individual farmers, influenced by factors such as soil fertility, water availability, market dynamics, and topographical features. The farmer communities inhabiting the basin also exhibit emergent properties in their cultural practices, social networks, and collective behaviors. Cultural traditions, such as water-sharing agreements, farming techniques, and community-based resource management practices, emerge from the interactions between individuals, families, and social institutions over time (Schnegg, 2018). For example, in groundwater irrigation cooperatives, responsible for managing groundwater resources, a number of cooperative leaders implement rules that would inhibit water use for the second crop planted during the season, if the initial crop is water demanding crop such as sugar beets or corn. These types of rules would result in reducing groundwater usage through collective behavior.

The Konya Closed Basin faces several challenges related to water scarcity, climate change and soil degradation. Since early 2000s farmers have been implementing advanced irrigation methods such as drip irrigation and sprinklers for corn, sugar beets and wheat irrigation. Increasing water efficiency in the groundwater dependent basin is a key method to progress towards achieving resiliency. At the same time, no-till practices, crop rotation and cover crops are implemented to improve soil quality and to reduce erosion in the basin. The collaborative water management to reduce groundwater use observed in some groundwater cooperatives can also be regarded as path towards increased resilience (Uygur, 2023).

4.3. Alternative Approaches for Sustainable Agriculture Using CAS Principles

Viewing the Konya Closed Basin as a complex adaptive system—characterized by interdependent actors such as farmers, ecosystems, and government agencies, all continuously adapting to shifting conditions like water availability, climate change, and economic incentives—is essential for breaking the negative feedback loops discussed earlier. To promote sustainable land use within this system, policies must focus on ecosystem-based approaches that account for feedback loops, adaptation, and resilience across agricultural, social, and ecological domains. By shifting away from intensive agriculture toward practices such as Integrated Pest Management (IPM), precision farming, conservation agriculture, and agroforestry, the Konya Basin can transition from negative feedback loops of water depletion and soil degradation to positive adaptive cycles. Encouraging the adoption of agroecological techniques helps the system adapt to climate variability while promoting resilience. These practices, such as crop diversification, agroforestry, and organic farming, align with the CAS attributes of emergence (local interactions leading to system-level change) and adaptation (adjusting to changing resource availability). Implementation of agroforestry integrates trees into agricultural landscapes, promoting system diversity while enhances connectivity between different system components—trees, crops, and soil (Dollinger and Jose, 2018). Trees help stabilize soil and retain moisture, allowing more efficient water use and improved soil health, which contribute to system resilience (Pantera et al., 2021).

Introducing rotational grazing practices may help prevent threshold effects like overgrazing and land degradation. By introducing flexibility into grazing patterns, the system can adapt to environmental stress, reducing risks of long-term damage (Millennium Ecosystem Assessment, 2005). Addressing desertification by planting native vegetation, stabilizing soil, and using cover crops prevents irreversible tipping points in the system. Non-linearity is a key feature of CAS—small interventions, such as restoring vegetation, can lead to significant improvements in soil and water retention over time. Local innovations that emerge can be rapidly shared and adopted across the region, promoting system-wide resilience.

IPM is a holistic approach to controlling pests that minimizes the use of harmful pesticides, promoting ecological balance and resilience within the system (Barzman et al., 2015). Using natural predators (e.g., beneficial insects) to control pests rather than chemical pesticides reduces harm to soil and water systems, maintaining the adaptive capacity of the agro-ecosystem. Techniques like crop rotation and intercropping disrupt pest cycles and enhance soil health, creating positive feedback loops that promote biodiversity and emergent ecological benefits over time (Hawes et al., 2021). By reducing reliance on expensive pesticides and focusing on natural controls, farmers can decrease costs and prevent the buildup of chemical residues in soils, aligning the system with long-term adaptability. Similarly, by applying only the necessary amount of inputs (fertilizer, water, etc.), precision farming creates feedback loops that reduce both resource use and costs, while increasing productivity (Pretty and Bharucha, 2014). Precision irrigation systems like drip irrigation or automated sprinkler systems use sensors and remote monitoring to adjust water application to crop needs, reducing water waste. This helps slow the depletion of groundwater and builds resilience by conserving water resources. In precision agriculture, the use of satellite imagery, soil moisture sensors, and other tools allows farmers to make adaptive decisions based on real-time feedback, aligning farming practices with the CAS principles of real-time adaptation and emergence of new techniques through local learning.

In a CAS, decision-making is often decentralized, with multiple stakeholders involved. Strengthening community-based approaches and engaging farmers in the decision-making process enhances local adaptation and self-organization (Ensor et al., 2016; Moraes et al., 2023). The groundwater irrigation cooperatives and surface water irrigation unions create networks of distributed control, where local farmers monitor and manage their water resources. This approach increase local adaptation to changing conditions. These community-based management opportunities also foster knowledge share between farmers leading to emergence of new, sustainable practices that can spread across the system, improving the overall resilience (Moraes et al., 2023).

Resilient and sustainable farming practices are essential in the Konya Basin to ensure long-term food security because the region faces significant environmental challenges, including water scarcity, soil degradation, and the impacts of climate change. Current intensive agricultural practices, which rely heavily on groundwater for irrigation, are depleting the basin’s water resources at an unsustainable rate, threatening the viability of agriculture and the local food supply. Sustainable practices like dry farming and improved grazing management reduce dependence on irrigation and help conserve water, making agriculture more resilient to drought. The socio-economic impacts of food insecurity are profound, with ripple effects on the local economy, employment, food prices, and social stability, underscoring the need for proactive strategies to ensure food security in the face of environmental challenges (Kan et al., 2018; Islam, 2022).

5. Conclusion

Complex Adaptive systems are non-linear, dynamic and do not inherently reach fixed equilibrium points. These systems are composed of independent agents whose behavior as reflected in their rules, are not homogeneous and, therefore, their goals and behaviors are likely to conflict - these conflicts or competitions tend to lead agents to adapt to each other's behaviors. Agents or decision-makers are intelligent, learn as they experiment and gain experience, and change behaviors accordingly. Thus, overall system behavior inherently changes over time. Adaptation and learning tend to result in self-organizing and patterns of behavior that emerges rather than being designed into the system. There is no single point of control, systems' behaviors are often unpredictable and uncontrollable, and therefore no one is "in charge".

Agricultural systems, such as those in Konya Closed Basin, exhibit defining characteristics of CAS: non-linearity, heterogeneity, adaptiveness, and dynamism. The CAS framework provides a valuable lens for analyzing interactions at different organizational levels—from individual farmers to ecosystem-wide patterns—and highlights how these interactions shape the broader agricultural landscape. Viewing the Konya Basin as a CAS offers a nuanced approach to managing land and water resources, enabling policymakers to appreciate the complex interconnections between agricultural activities, environmental factors, and socio-economic influences.

This perspective is particularly relevant in addressing the basin’s challenges, including climate change, land use change, food security, and intensive agriculture. As climate change intensifies and water resources become more strained, policies must embrace the inherent adaptability and emergent behaviors of agricultural systems. By promoting ecosystem-based production systems, such as agroecology and sustainable land management, and regulating groundwater extraction, decision-makers can enhance the resilience and sustainability of the basin’s agricultural practices.

Future research should explore the long-term impacts of climate change on the basin’s agricultural systems, including shifts in crop viability and water availability. Additionally, the potential for ecosystem-based approaches to improve the basin’s adaptive capacity warrants deeper investigation. Policies that encourage decentralized, participatory governance, and innovation can further strengthen the system’s ability to respond to uncertainties, ensuring the long-term sustainability of the region’s natural resources and food production systems.

The insights gained from studying the Konya Closed Basin through the CAS framework can serve as a blueprint for addressing similar challenges in other regions, advancing our understanding of sustainable agricultural management in the face of global environmental change.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	IDÇ
C	100
D	100
L	100
W	100
CR	100
SR	100

C=Concept, D= design, S= supervision, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The author declared that there is no conflict of interest.

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