Resilience in Agroecosystems: An Index Based on a Socioecological Systems Approach

ANDREA SUAREZ-PARDO, CLARA VILLEGAS-PALACIO, AND LINA BERROUET

a Departamento de Geociencias y Medio Ambiente, Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín, Medellín, Antioquia, Colombia

b Grupo de Investigación en Ecología Aplicada, Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia, Medellín, Antioquia, Colombia

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ABSTRACT: This article presents an agroecosystem resilience index (ARI) relative to two types of exogenous drivers: biophysical and socioeconomic threats. The ARI is based on a theoretical framework of socioecological systems and draws upon multicriteria analysis. The multicriteria consist of variables related to natural, productive, socioeconomic, and institutional systems that are weighted and grouped through expert judgment. The index was operationalized in the Rio Grande basin (RGB), in the Colombian Andes. The ARI was evaluated at the household level using information from 99 RGB households obtained through workshops, individual semistructured interviews, and surveys. The ARI is a continuous variable that ranges between 0 and 1 and results in five categories of resilience: very low, low, medium, high, and very high. When faced with climate change impacts, 19% of households showed low resilience, 64% showed medium resilience, and 16% showed high resilience according to the ARI. When faced with price fluctuations, 23% of households showed low resilience, 65% showed medium resilience, and 11% showed high resilience. Key variables associated with high resilience include the diversity of vegetation cover, households that have forests on their properties, a high degree of connectivity with other patches of forest, diversification of household economic activities, profitability of economic activities, availability of water sources, and good relationships with local institutions.

KEYWORDS: Social Science; Climate change; Indices; Measurements; Ecological models; Ecosystem effects; Resilience

1. Introduction

Societies and nature are interdependent and should be considered integrated socioecological systems (Jodha 1998; Sterk et al. 2017). The framework of socioecological systems (SES) addresses the interactions between ecosystems and humans through ecosystem services (Collins et al. 2011). Ecosystem services are defined as the benefits people obtain from ecosystem functions (Millennium Ecosystem Assessment 2005) or the aspects of ecosystem functions used (actively or passively) to produce human well-being (Fisher et al. 2009). Despite this interdependence, human activities have negatively affected the environment. These effects on ecological systems affect their functioning and, therefore, their potential supply of ecosystem services, generating consequences for human well-being (Duraiappah et al. 2005; Resilience Alliance 2010).

Transformations in ecological integrity and the importance of ecosystem services for human well-being highlight the need for information (i.e., indicators) and strategies for sustainable management of SES (Martín-López et al. 2006). The drivers of change affecting socioecological systems can be in the biophysical or socioeconomic and cultural arenas. Climate change is an exogenous driver of change in the biophysical arena. A change in the price of agricultural products or inputs in agricultural production is an exogenous driver of change in the socioeconomic and cultural arena. However, the drivers of change do not always affect ecosystem functions and/or human well-being. Whether ecosystem functions and human well-being are affected or not depend on the magnitude of the disturbances and the response characteristics of the system, such as its vulnerability and resilience (Berrouet et al. 2018). Resilience is a property of SES with multiple definitions in literature. It has been defined as the ability of an SES to face change and, meanwhile, continue to develop (Sterk et al. 2017).

Agroecosystems are natural ecosystems modified by human-kind to produce goods or raw materials (Zuluaga et al. 2011) or provide a specific provisioning service (food, fuel, and fiber) (Zabala et al. 2021). Agroecosystems have an integral function: they must not only produce goods (crops, animals, eggs, milk, and fibers) but also provide habitat services for humans and animals, ecological functions (nutrient cycling, biotic regulation, carbon capture, erosion control, and detoxification of the environment), landscape maintenance, conservation of plant, and animal biodiversity (Sarandón and Flores 2014).

Agroecosystems encompass the interaction of agricultural activities, biophysical processes, and individual or collective decisions. They are susceptible to unpredictable natural events, including changes in climate and diseases and changes in economic factors, such as demand, price fluctuations, policy variations, and social pressure from culture and tradition (Vargas Betancur 2020).

Agroecosystems can also be considered as the result of coevolution between social and natural systems or the result of interactions between producers and their knowledge and their biophysical and socioeconomic environment (Sarandón and Flores 2014). Therefore, agroecosystems can be analyzed from the perspective of socioecological systems (Cabell and Oelofse 2012).
One of the pressures that can be considered in agroecosystems in the global south is associated with the intensive change in land use. This change in land use has mainly favored the supply of provisioning ecosystem services, such as food production through agricultural and livestock systems. This is particularly important in the basins of the tropical Andes and countries like Colombia where most of the population and important economic activities (such as agriculture and livestock) are in mountainous areas. These activities are necessary to supply the population’s food consumption (Cubasch et al. 2013; Preston 1996).

Studies of resilience in agroecosystems have been increasing in recent years (Cetinkaya Ciftcioglu 2017; Cleves 2018; Linstädter et al. 2016; Srinivasa Rao et al. 2019). Cabell and Oelofse (2012) argued that, in the context of agroecosystems, resilience arises from the unique interaction between the manager of the agroecosystem, the agroecosystem itself, and the context in which it is involved. In this case, resilience can be considered as the ability of the agroecosystem to face endogenous and exogenous pressure and continue providing ecosystem services and sustaining the well-being and quality of life levels of human communities.

From the conceptual framework of complex adaptive systems, the study and measurement of resilience as a property provides an understanding of what attributes of the socioecological system allow it to absorb disturbances, reorganize, learn, and adapt in the context of change to maintain the essential elements of the system (Carpenter et al. 2001; Vázquez-González et al. 2021). In addition to the complexity of the systems, one of the possible reasons of the difficulty to analyze resilience in an SES is the absence of indicators for evaluating resilience (Cai et al. 2018). A resilience index would allow the detection of transitions in agroecosystems in which changes in one or more of its attributes reduce (or do not reduce) the agroecosystem’s ability to recover and adapt in the case of a disturbance and maintain the essential elements of the agroecosystem. The information provided by these indices guides territorial planning processes that improve the conditions of the system’s attributes to strengthen resilience. Further, assessing resilience in an SES can provide information about the developing strategies to cope with known and unexpected changes in ecosystems (Resilience Alliance 2010; Desjardins et al. 2015).

However, there is still no consensus on how to evaluate resilience. Various assessment frameworks have emerged, but their applicability is yet to be critically evaluated (Douxchamps et al. 2017). Resilience has been used as a framework to understand sustainability challenges in various ecosystems, but it has not been systematically applied across the range of systems, specifically those used for food and fiber production in terrestrial, marine, and freshwater environments (Rist et al. 2014). There could be two ways of evaluating resilience. An ex ante evaluation would focus on anticipating the capacity of the system to face a disturbance and continue developing. This evaluation is based on the state of a set of attributes of the system that enhance resilience and would be performed before the disturbance. Conversely, an ex post evaluation would focus on evaluating the performance of the system after it has faced the disturbance. The ex post resilience evaluation would be a validation of the ex ante resilience assessment, which means verifying whether the units that were predicted to be resilient in the ex ante evaluation were resilient after the shock. This work focuses on the ex ante evaluation.

This work proposes the development of a single multidimensional index that considers the indicators proposed by Cabell and Oelofse (2012) and applies the indicators to agroecosystem contexts in tropical watersheds. This type of information is relevant in a context such as that of the tropical Andes, in which resilience studies and evaluations have not been conducted under the SES approach or from a holistic perspective that implies an SES facing changes because of certain interventions in ecosystems.

Assessing the resilience of a socioecological system requires 1) defining the type of threat the system faces (Carpenter et al. 2001) and 2) specifying the spatial scale of the analysis (Bennett et al. 2005; Carpenter et al. 2001; López-Ridaura et al. 2000). The multidimensional agroecosystem resilience index (ARI) allows the assessment of the resilience of an agricultural production system to natural disturbances, which cannot be fully controlled, and exogenous socioeconomic disturbances. It was applied to households located in the Rio Grande basin, Colombia. Twenty-one variables, synthesized in four categories, were identified and validated by a group of experts as determinants of resilience. Each agroecosystem corresponds to a type of socioeconomic profile previously identified by Berrouet et al. (2019). The index is built with the weighting obtained from the group of experts. Two indices are obtained, one for the threat of climate change and the other for the threat of price changes. In the second section of this paper, we present the methods used in the research. The third section describes the results, and the last part presents the conclusions and some future lines of research in this field.

2. Methods

The ARI is a weighted combination of categories and variables. It was developed to analyze resilience against the threat of climate change (hereinafter threat 1) and against the threat of price changes (hereinafter threat 2) for inputs and final products. Figure 1 presents the methodological pathway used to build the index. This section presents the five phases that correspond to developing the index, which are detailed below.

Development of the ARI began with a literature review to identify the categories and variables that determine resilience; then, these categories and variables were validated and weighted using a focus group of experts. We adopted the definition of resilience proposed by Sterk et al. (2017), which, in terms of the SES, means that the ecosystem functions are not altered when facing drivers of change, and consequently, preserve the potential provision of ecosystem services, or the social system does not suffer a loss of well-being when facing a change. This was explained to the experts in the survey.

Subsequently, we proceeded with the selection of the households in which the index was evaluated. For this, databases of different research in the study area were used, and
ARI was evaluated in each agroecosystem. In this paper, a producer household is considered as an agroecosystem. The spatial scale of analysis is the household/farm level. The households are considered as agroecosystems because the land holder manages the land and the forms of food production.

a. Case study: Rio Grande basin

The Rio Grande basin (RGB) is situated in the northwestern region of Colombia, as shown in Fig. 2. The total area of the RGB is approximately 127,896.29 ha (1278.96 km²), 61.62% of which include pastures mainly dedicated to dairy farming; 28.99% are forest areas, páramos, forest plantations, and shrublands in different stages of succession with productive and protective uses; 1.54% is dedicated to transitory crop agriculture, such as potatoes (Solanum tuberosum ssp. Andigena) and crops, tamarillo (Cyphomandra betacea Cav. Sendt), avocado (Persea americana Mill.), and coffee (Coffea arabica L.). The remaining 7.85% corresponds to infrastructure, small mining processes, bodies of water, and degraded areas (CORANTIOQUIA 2015).

The total population in the RGB is approximately 68,000 inhabitants. The main sources of income are dairy farming, poultry farming, raising pigs, and, to a lesser extent, agricultural activities, such as potato crops, tamarillo, and coffee in the lower part of the basin. In urban areas, the development of agribusiness services that support agricultural and livestock activities is the main source of income. The Rio Grande II reservoir is located within the RGB, which is the source of water and power for a significant percentage of the population of

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**FIG. 1.** Methodological pathway for the construction and evaluation of the resilience index.

**FIG. 2.** Location of the Rio Grande basin, Department of Antioquia, Colombia. Source: Machado et al. (2019), used with permission.
the second-most populated urban center in the country (Área Metropolitana del Valle de Aburrá). Considering the strategic importance of this area, a series of plans, programs, and policies have been designed over the past 15 years to restore and conserve strategic ecosystems for the region (Bolaños 2017). These activities are a part of defining the agroecosystems on which this research focuses.

1) Threat 1: Climate change

The risks or effects of climate change on socioecological systems are especially important in the hydrographic basins of the tropical Andes, which provide multiple environmental services, such as water for human consumption, and where the main production activities and vast majority of the population are located (García Múnera et al. 2016).

For the case study addressed in this project, García Múnera et al. (2016) analyzed the trends in precipitation and temperature series of the RGB in Antioquia, Colombia, to detect the possible signs of climate change and contribute to risk management in the region. The temperature trends are increasing and statistically significant throughout the basin. This result shows that the region is warming up by approximately 0.4°C decade⁻¹, which may be due to climate change or local factors (García Múnera et al. 2016).

2) Threat 2: Price changes

In Colombia, there is evidence of deterioration in the profitability of dairy farmers between January 1995 and June 2005 because while costs increased by 303% the price of milk was only 207% higher even with inflation (Ramírez and Vásquez 2009). The Colombian Federation of Livestock Farmers (FEDEGAN) reported that the cost of milk production per liter in Antioquia for 2018 increased by 3.4% in comparison with 2015. This threat can affect both the sale prices of the product and the prices of production inputs.

b. Identifying conceptual approaches to resilience, variables, and categories for their evaluation

This research was based on the conceptual frameworks and operational advances in resilience and socioecological systems. Understanding the connection of resilience to the sustainability of the biosphere, ecology, and ecosystems is critical (Folke 2016; Standish et al. 2014; Jodha 1998). If that connection is understood, the ecosystems can be optimally managed through social mechanisms to build resilience and ways to manage socioecological dynamics (Jodha 1998; Standish et al. 2014; Sterk et al. 2017). Despite the important connection, the sustainability of an SES is not equivalent to SES resilience. Both concepts include variables of different types of capital but are not equivalent. Natural capital is related to natural resources and the biophysical system, whereas human-made capital can be reproduced by human beings (Barinaga-Rementería 2020). Sustainability refers to maintaining the stock of capital in the SES, whereas resilience refers to the capacity of the SES, with all types of capital, to face drivers of change and continue developing. All resilience measurements are not related to sustainability, all sustainability measures are not related to resilience. The term resilience is an indicator of the well-being of the SES (Desjardins et al. 2015; Harger and Meyer 1996). Therefore, resilience has a broader meaning in sustainability science because it encompasses the capacity to adapt, transform, and learn (Carpenter et al. 2001). A resilient agroecosystem can continue providing vital services if it is challenged by natural disturbances (Taylor et al. 2013).

c. Phase I: Selection of variables and categories

The definition of categories was based on the types of capital proposed in Scoones’s (1998) conceptual framework of sustainable livelihoods. These categories are consistent with those proposed by Srinivasa Rao et al. (2019), who developed agroecosystem-based sustainability indicators for climate-resilient agriculture in India. The categories for analyzing resilience of an agroecosystem include ecological, social, economic, and political (Darnhofer 2014). Variables within each category are presented in the results section.

d. Phase II: Validation and weighting of the categories and variables for both threats by experts

As stated by Villegas-Palacio et al. (2020), “in the process of developing the composite indicator, weighting variables is an important step because each of them is expected to describe the state of the system in a different way.” The weighted arithmetic mean is among the most commonly used techniques of the multiple criteria decision-making techniques that have been applied to various problems related to environmental analysis. These have been combined with group decision-making techniques in which different experts are required to express their preferences to assign weights to the different variables without resorting to more sophisticated methods (Díaz-Balteiro et al. 2017).

To weigh the selected categories and variables, the expert focus group method was used, which is a systematic technique to collect the scientifically valid opinion of experts on a given topic (Munaretto et al. 2013). This technique is recognized in qualitative research and allows members to provide their opinions from experience, plurality, and contrast of opinions (Bertoldi et al. 2006). This validation was achieved through individual interviews, with communication between the researcher and expert. In the survey, the description of each category and variable was presented for developing the resilience indices against the aforementioned threats (survey available upon request). In the individual interviews, each expert, according to their knowledge and experience, answered the survey to assign weight to each category and variable to be evaluated against the two threats.

The group of experts was selected on the basis of their knowledge in SES, agricultural production systems, resilience, and the study area as well as experience about issues related to this research in agroecosystems. This group comprised nine experts, including men and women. Among them, five were professors from the National University of Colombia, Medellín, and four were professionals who worked with and belong to organizations that have developed sustainability and restoration strategies for agricultural systems in the case.


study area, such as Grupo Habitat, Territory, and Environment [Habitat, Territorio, y Medio Ambiente (HTM)] and the Center for Research in Sustainable Agricultural Production Systems [Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria (CIPAV)].

We explained the weighting system to the experts, in which they must provide the weight of importance of the categories and the variables for threat 1 (A1) and threat 2 (A2). The experts, according to their criteria, weighed the categories and variables. Each category and variable can have two different weights, one for each threat, because a system can be resilient in a different way to each type of threat (Carpenter et al. 2001). Further, each category and variable may have a different importance in their resilience against each threat. The weighing is based on the concept that not all system components have a similar effect on resilience against the occurrence of a disturbance (Cleves 2018; Kaly et al. 2004). The weighting of categories and variables by experts were averaged to assign a corresponding weight to each and generate the structure of the indices.

e. Phase III: Development of the ARI for threat 1 and threat 2

Two agroecosystem resilience indices were developed, one against climate change, ARI 1 (threat 1) and the other against price changes, ARI 2 (threat 2), according to the weights of the variables and categories. The climate change resilience index, ARI 1, measures the degree to which the agroecosystem can face changes in temperature and/or precipitation and continue operating by supplying ecosystem services and their associated benefits. The price change resilience index, ARI 2, measures the degree to which the agroecosystem can face changes in prices of agricultural products and/or inputs for agriculture production and continue operating by supplying ecosystem services and their associated benefits.

Both indices contain the same categories and variables. However, each one’s weights are different. Equation (1) presents the general structure for each category against threat 1, and Eq. (2) presents the general structure for each category against threat 2. Both equations show that the value of each category is assigned by the weighted sum of the variables composing it. The index ranges between 0 and 1:

\[
\text{Cat}_j = (W1_{\text{Var1}} \times \text{Var1}) + (W1_{\text{Var2}} \times \text{Var2}) + \cdots + (W1_{\text{Vari}} \times \text{Vari})
\]

(1)

\[
\text{Cat}_j = (W2_{\text{Var1}} \times \text{Var1}) + (W2_{\text{Var2}} \times \text{Var2}) + \cdots + (W2_{\text{Vari}} \times \text{Vari}),
\]

(2)

where \(W1_{\text{Vari}}\) is the weight of variable \(i\) against threat 1, \(W2_{\text{Vari}}\) is the weight of variable \(i\) against threat 2, and \(\text{Vari}\) is the value of variable \(i\), with \(i\) being the variables of category \(j\).

The general structure of the ARI for the threat of climate changes, ARI1, is given by Eq. (3), and the resilience index in an agroecosystem for the threat of price changes, ARI2, is given by Eq. (4):

\[
\text{ARI1} = (w1\text{Cat}_1 \times \text{Cat1}) + (w1\text{Cat}_2 \times \text{Cat2}) + (w1\text{Cat}_3 \times \text{Cat3}) + \cdots + (w1\text{Cat}_j \times \text{Cat}j)
\]

(3)

\[
\text{ARI2} = (w2\text{Cat}_1 \times \text{Cat1}) + (w2\text{Cat}_2 \times \text{Cat2}) + (w2\text{Cat}_3 \times \text{Cat3}) + \cdots + (w2\text{Cat}_j \times \text{Cat}j),
\]

(4)

where \(w1\text{Cat}_j\) is the weight of category \(j\) against threat 1, \(w2\text{Cat}_j\) is the weight of category \(j\) against threat 2, and \(\text{Cat}_j\) is the value of category \(j\).

f. Phase IV: Selection of households/agroecosystems

To select households, we worked with the database that was consolidated from the research conducted by Berrouet et al. (2020), Machado et al. (2019), and Villegas-Palacio et al. (2020). The database of Berrouet et al. (2020) comprises 172 households. The information was collected by conducting semistructured interviews, workshops, and surveys with people from the RGB in two phases during the 2015/16 period. This database contains information about the households in variables, such as ecosystem services (property identification, location, and georeferencing), the socioeconomic profile of the households (socioeconomic characteristics, infrastructure, access to services, among others), the productive profile (size of the property; distribution of productive activities, production costs, production level, among others), the institutional relationship and participation of stakeholders in institutions and networks, the use of ecosystem services (use of water, soil, and forest), and finally, the replacement capacity of the ecosystem service (scenarios of ecosystem service reduction, adaptive capacity, technological barriers, and perception).

g. Phase V: Index evaluation

We proceeded with the evaluation by operationalization, which meant calculating the structure of both indices [Eqs. (1)–(4)].

3. Results

a. Categories and variables with respective weights

As presented in Table 1, the 21 variables that compose the ARI are classified into four categories with the respective weights from the experts against each threat and each one’s description and measurement.

The first category is the natural system, comprising five variables. This category includes characteristics related to the soil (its composition and vulnerability), the land-cover vegetation found in the ecosystem, the soil’s properties (such as water holding capacity) and ecological characterization, which means the biophysical characteristics in which the agroecosystem is found (such as forest connectivity).

The second category is the productive system, comprising five variables, including the main characteristics required by...
an agricultural activity for operation, such as the use of agrochemicals, availability of water sources, and demand for water. Knowing how many agricultural activities are conducted per household is also essential. Considering the productive functions of an agroecosystem is one way to operationalize resilience (Peterson et al. 2018).

The third category, called the socioeconomic system, reports certain aspects of an individual’s living condition in

<table>
<thead>
<tr>
<th>Categories’ weight</th>
<th>Price change</th>
<th>Variable</th>
<th>Description</th>
<th>Categories’ weight</th>
<th>Price change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category: Natural system</td>
<td></td>
<td>Soil cover (CS)</td>
<td>Layer of vegetation covering the ground</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Homogeneity in the percentage of area in each land-cover vegetation in the farm (HCS)</td>
<td>Similarity in the proportion of area covered by each type of land-cover vegetation</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Approximate forest connectivity (ACB)</td>
<td>Distance from farm to the nearest forest patch</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soil vulnerability (VS)</td>
<td>Loss of soil capacity to maintain ecosystem functions</td>
<td>0.21</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Available water retention capacity (CRA)</td>
<td>Water storage capacity of the soil</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Category: productive system</td>
<td>0.26</td>
<td>Use of agrochemicals (UA)</td>
<td>Application of agrochemicals for economic activities</td>
<td>0.18</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td>Productive activities (AP)</td>
<td>Number of productive activities on the farm</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td>Homogeneity of economic activities (HAP)</td>
<td>Similarity in the proportion of area dedicated to each economic activity on the farm</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td>Availability of water sources (DFA)</td>
<td>Number of water sources that the farm can use</td>
<td>0.2</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td>Water demand (DA)</td>
<td>Amount of water needed by the farm to guarantee the economic activities</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>Category: socioeconomic system</td>
<td>0.25</td>
<td>Profit level (NB)</td>
<td>Annual farm profit</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Access to technology and innovation (ATI)</td>
<td>Use of new technologies in economic activities</td>
<td>0.2</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Ecological knowledge (CE)</td>
<td>Knowledge of ecological processes in the territory</td>
<td>0.19</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Access to insurance (AS)</td>
<td>Access to insurance that protects the farmer in case of losses</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Credit access (AC)</td>
<td>Access to credit for future investments or to respond to shocks</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Productive activity training (CAP)</td>
<td>It refers to the technical consultancies or training of the productive activity in which the household participates</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Education (E)</td>
<td>Household skills to access information that allows them to adapt and facilitate decision-making</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>Category: institutional system</td>
<td>0.2</td>
<td>Information distribution (DI)</td>
<td>It refers to the mechanisms of the territorial entities to reach the communities and provide relevant information in the context of SE</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>Conservation mechanisms (MC)</td>
<td>Access to institutional-type mechanisms used by the household for the conservation of the ecosystem</td>
<td>0.24</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>Household institution relationship (RIB)</td>
<td>Presence and support of the institutions to the households</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>Community organization (OC)</td>
<td>Social networks in which a household participates</td>
<td>0.32</td>
<td>0.32</td>
</tr>
</tbody>
</table>
terms of their social and economic level. It also integrates some of the mechanisms, such as training, knowledge, and technologies that allow individuals to be aware of the environment in which they live, as well as the consequences of their activities.

Socioeconomic conditions provide relevant information for maintaining the benefits provided by agroecosystem services (Lescourret et al. 2015). The fourth category, the institutional system, includes the interactions between institutions and the population. Institutions refer to public and private organizations that act in the territory. These include social rules and regulations, which can indicate self-organization in an SES. In addition, this category reports the mechanisms and forms of organization within the communities to achieve objectives, which contribute on an individual level and facilitate collective action. The institutional system is essentially a binding force for the other categories (Cabell and Oelofse 2012; Ifejioka Speranza et al. 2014; Srinivasa Rao et al. 2019; Villegas-Palacio et al. 2020). The variables and results of this category were given by Villegas-Palacio et al. (2020), because they coincide with the ones we used in the adaptation capacity index. The values of the ARI vary between 0 and 1, with 1 being the most resilient households and 0 being the least resilient ones.

Table 1 shows that the category of greatest importance for experts considering the threat of climate change is the natural system. With regard to the threat of price changes, the category of greatest importance was the socioeconomic system, followed by the productive system. The institutional category is more important in this threat than in the face of climate change. It is observed that the natural system category is the least important with respect to price changes.

In the natural system, the soil-cover variable is the most important for experts in the threat of climate change, followed by the water holding capacity. This is consistent with the fact that the amount of soil cover contributes to the diversity and redundancy of species and landscapes. The variable that had the greatest importance in the threat of price changes is the vulnerability of the soil. The more vulnerable the soil, the greater are the monetary efforts required to prepare the desired soil conditions for production.

In the productive system, the weights of the variables for the threat of climate change have similar values, varying in the range of 0.15–0.23. In this case, two variables have the same, highest weight in the category—productive activities and demand for water. An agroecosystem can better cope with the threat of climate change if its productive activities are diverse (Altieri et al. 2015). The weight of the variables for the threat of price changes varies in the range of 0.16–0.29, with the use of agrochemicals as the most important for experts.

In the socioeconomic system, in the case of the threat of climate change, the most important variable is that of access to technology and innovation, followed by ecological knowledge. These variables contribute to the principles of promoting learning by acquiring new information and combining different types of knowledge for better management of complex ecosystems, including different knowledge systems and their combination (Jodha 1998). In the case of the threat of price changes, the most important variable for experts was profit level, followed by access to technology. The change in prices directly affects the profit level variable because it directly affects the income and expenditures of the agroecosystem.

Last, in the institutional category, the weights are similar for three of the four variables in threats. For both threats, community organization was the most important variable. Community organization allows creating bonds of trust, access to information, and exchanges of experience and knowledge (Folke et al. 2002). With this information, the experts weighted the categories and variables differently against each threat with their knowledge and experience.

b. ARI

Eqs. (5)–(12) use the weights shown in Table 1. These belong to each category evaluated against each threat, as shown below:

\[
\text{NAT}_A1 = 0.25(\text{CS}) + 0.15(\text{HCS}) + 0.18(\text{ACB}) + 0.21(\text{VS}) + 0.22(\text{CRA}),
\]

\[
\text{NAT}_A2 = 0.19(\text{CS}) + 0.15(\text{HCS}) + 0.15(\text{ACB}) + 0.28(\text{VS}) + 0.23(\text{CRA}),
\]

\[
\text{PRO}_A1 = 0.18(\text{UA}) + 0.23(\text{AP}) + 0.15(\text{HAP}) + 0.20(\text{DFA}) + 0.23(\text{DA}),
\]

\[
\text{PRO}_A2 = 0.29(\text{UA}) + 0.21(\text{AP}) + 0.17(\text{HAP}) + 0.18(\text{DFA}) + 0.16(\text{DA}),
\]

\[
\text{SOC}_A1 = 0.14(\text{NB}) + 0.20(\text{ATI}) + 0.19(\text{CE}) + 0.08(\text{AS}) + 0.11(\text{AC}) + 0.15(\text{CAP}) + 0.13(\text{E}),
\]

\[
\text{SOC}_A2 = 0.21(\text{NB}) + 0.19(\text{ATI}) + 0.13(\text{CE}) + 0.10(\text{AS}) + 0.12(\text{AC}) + 0.13(\text{CAP}) + 0.12(\text{E}),
\]

\[
\text{INST}_A1 = 0.21(\text{DI}) + 0.24(\text{MC}) + 0.23(\text{RIB}) + 0.32(\text{OC}), \text{and}
\]

\[
\text{INST}_A2 = 0.23(\text{DI}) + 0.22(\text{MC}) + 0.23(\text{RIB}) + 0.32(\text{OC}).
\]
changes, INST_A1 is the equation of the institutional system category in the threat of climate change, and INST_A2 is the equation of the institutional system category in the threat of price changes.

The result of each equation by category against each threat is part of the resilience index, as shown by Eqs. (13) and (14):

\[
ARI1 = 0.29(\text{Nat}_A1) + 0.26(\text{Pro}_A1) + 0.25(\text{Soc}_A1) + 0.20(\text{Inst}_A1)
\]

\[
ARI2 = 0.16(\text{Nat}_A2) + 0.29(\text{Pro}_A2) + 0.32(\text{Soc}_A2) + 0.23(\text{Inst}_A2)
\]

where ARI1 is the resilience index for the threat of climate change and ARI2 is the resilience index for the threat of price changes.

Notably, there is a category that represents a greater weight in the index in the face of each threat. When facing the threat of climate change, it is the natural system and when facing the threat of price changes, it is the socioeconomic system. It can also be observed that the institutional system has a greater weight for the threat of climate change than that for the threat of price changes. This system also affects the response of the agroecosystem to the threat of price changes.

c. Index evaluation

1) Selecting households

For this research, some of the households found in Berrouet et al.’s (2020) database were selected. For the selected households there is information on the selected variables, which are necessary to operationalize the resilience indices to both threats. The information on the variables was found in the Berrouet et al. (2020) database, where the values of each variable were subtracted and normalized according to the measurement scale. Berrouet et al. (2020) conducted fieldwork and used workshops, interviews, and surveys to collect the information.

ArcGIS and Excel software were used to collect data about the variables of the natural system, as well as the sources of information from previous research conducted in the study area (Machado et al. 2019; Cleves 2018, Berrouet et al. 2020). The soil-cover (CS) variable was taken from Berrouet et al.’s database, as well as the indicator of homogeneity of land-cover proportions (HCS). The variables of soil vulnerability (VS) and available water holding capacity (CRA) were taken from the database built by Machado et al. (2019), where the authors determined the vulnerability of the soil’s natural capital to environmental change. The forest connectivity approximate (ACB) variable was developed with the connectivity parameters established by Cleves (2018) using the ArcGIS software applied to the database by Machado et al. (2019).

To evaluate Eqs. (5)–(14), a total of 99 households were selected for the case study. The selected households (99) exhibit spatial representation and diversity in the characteristics of the households. Figure 3 presents the location of the households selected to evaluate the ARI. Further, this figure presents the main uses and soil vegetation cover and their spatial distribution.

The selected households were classified based on their socioeconomic status. The classification resulted in the profiles of groups of households with homogeneous socioeconomic characteristics (Berrouet et al. 2019). In the case of territories with multiple economic activities and socioeconomic characteristics, the profiles of the households can be defined based on the main economic activity, the size of the land owned by each household, the diversification of land uses (percentage of land dedicated to a given use), the level of production, and the economic activity from which they derive most of their income. Identifying the profiles of the households is relevant because it allows establishing the mechanisms to collect information from each profile and property. Furthermore, this classification allows the analysis of the uniformity of the resilience index within each profile; therefore, it allows us to observe certain characteristics possessed by the most resilient households. Classifying households in profiles had three motivations.

The first motivation is that this classification was used in previous research in the basin. Table 2 shows this categorization of profiles, which was conducted by Berrouet et al. (2020). Berrouet et al. (2020) defined household profiles based on information acquired from 139 surveys they conducted and information from previous studies by Álvarez (2012) (182 households surveyed), López-Gómez (2012) (27 households interviewed), and Dávila Betancurth (2016) (17 households evaluated). Analyzing the resilience index of each household profile would allow us to relate the research reported in this paper to previous research by answering questions such as, Is there a relationship between the vulnerability and resilience of different household profiles?

The second motivation is that classifying users in profiles would allow analyzing the homogeneity of the resilience index within each profile and, therefore, allow the targeting of possible management strategies to strengthen the resilience of the less resilient profiles. The third motivation is that this classification helped to focus field work efforts on both sampling intensity and selecting the strategy for gathering information.

2) ARI results

As described in the development of the resilience index, the ARI is a continuous variable that ranges between 0 and 1. The closer the value of the ARI is to 0, the less resilient is the agroecosystem; the closer it is to 1, the more resilient is the agroecosystem. This is because of the variable’s definition and way of measuring it. This interval [0, 1] was divided into five categories, as shown in Table 3. We divided the interval into five categories and arbitrarily defined them to be able to classify the agroecosystems and compare them. However, these categories can be reformulated according to the purpose of the resilience analysis.

Table 4 presents the results of the index evaluations in the selected households. The table shows the number of households that belong to each level of resilience against the threats of climate change and price changes. No household had very
low resilience or very high resilience. The results were concentrated in three levels—low, medium, and high resilience.

Notably, in the face of climate change, a greater number of households have a high level of resilience, and a smaller number of households have low resilience in comparison with the results in the face of price changes. However, the results for both threats had a similar number of households in the medium resilience level.

The threat of price changes has a greater overall impact on households. This may be due to greater weight in the key variables affecting this threat, such as the level of benefits, use of agrochemicals, and vulnerability of the soil. Furthermore, if other variables that compose the index have a low value, the impact will be greater.

Tables 5 and 6 present the profiles of the households, level of resilience, number of households that make up said level per profile, and the percentage they represent in the threats of climate change and price changes, respectively. Table 5 shows that the profiles of small cattle breeders (PB4), medium cattle breeders (PB5), small commercial crop farmers (PB16), and indirect households of other activities (PB31) have approximately 60% of the households with medium resilience. However, most of the remaining profiles have households with medium resilience, except the profiles of medium and large foreign monoculture farmers (PB17) and large cattle breeders with more activities (PB30), which only have households with low resilience. Four profiles have households with high resilience, which are small cattle breeders (PB4), medium cattle breeders (PB5), small commercial crop farmers (PB16), and small and medium cattle breeders with more activities (PB29).

The results on the threat of price changes in Table 6 present differences in the profiles by level of resilience when compared with Table 5, as in the case of the profile of small cattle breeders (PB4), where there was an increase in households with medium resilience and a decrease in households with high resilience, that is, the threat of price changes has a greater impact on these households. Another interesting case is the indirect households renting (PB32) profile in Table 6, which increased the households with low resilience and decreased the households with medium resilience. This is because the characteristics of this profile are households that lease their land for others to work—they only get rental income. Following the previous idea that the threat of price changes has a greater impact on these households, if the tenants have a decrease in income, the owner’s income (household) is also affected.

For the profile of small and medium cattle breeders with more activities (PB29), Table 5 showed that these households have high resilience and Table 6 showed that these households have medium resilience. This is because price changes directly affect the income, possibly because the costs were higher than the income. However, it is the only profile that has no households with low resilience, perhaps because it represents a diversification of small- and medium-scale economic activities. To conclude, all the profiles except that of the small and medium cattle breeders with more activities (PB29) present households with low resilience.

Notably, there are profiles with greater resilience against both threats, as could be observed from the profile of small and medium cattle breeders with more activities (PB29). In the profiles of small cattle breeders (PB4), medium cattle breeders...
There are households at all levels of resilience, probably because of the combination of variables that present greater value and the weight that accompanies them, which helps to build resilience. The percentages in the previous tables (percentage with low resilience, percentage with medium resilience, and percentage with low resilience) help to clarify the representativeness of the levels of resilience by profile because the number of households is not homogeneous by household profile.

### 4. Discussion

This research presents the development of a resilience index in agroecosystems with threats of climate change and price changes. It is a composite index, which incorporates categories in line with the livelihoods and variables developed in conjunction with the indicators proposed by Cabell and Oelofse (2012). Some authors suggest that having a unique resilience value may not be as useful as understanding which attribute or attributes may determine a given resilience value (Darnhofer et al. 2010; Bennett et al. 2005). The index proposed in this paper allows understanding the factors that determine the results of resilience index evaluation. The categories and variables selected in this resilience index allow us to holistically study the agroecosystem by considering most of the measurable characteristics involved.

Our results are consistent with those of Altieri (1999), Altieri et al. (2015), Cabell and Oelofse (2012), Di Falco and

### TABLE 2. Household livelihood profiles in the study area. The table is adapted from Berrouet et al. (2018).

<table>
<thead>
<tr>
<th>Code</th>
<th>Livelihood profile</th>
<th>Description</th>
<th>No. households</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB4</td>
<td>Small-size cattle breeders</td>
<td>Production level: between 0 and 410 L day(^{-1}) of milk; land area lower than 10 ha, around 70% of it in pastures and around 30% in subsistence agriculture</td>
<td>48</td>
</tr>
<tr>
<td>PB5</td>
<td>Midsized cattle breeders</td>
<td>Production level between 410 and 1000 L day(^{-1}) of milk; land area between 10 and 30 ha, around 80% in pastures and around 20% in other agricultural and livestock activities</td>
<td>12</td>
</tr>
<tr>
<td>PB6</td>
<td>Large-size cattle breeders</td>
<td>Milk cattle householding, production level greater than 1000 L day(^{-1}) of milk; land areas greater than 30 ha with more than 90% in pastures</td>
<td>8</td>
</tr>
<tr>
<td>PB16</td>
<td>Small-scale producers of commercial crops</td>
<td>Small householders producing corn, beans, vegetables, and fruit trees for local markets; these householders are no organized in cooperatives</td>
<td>9</td>
</tr>
<tr>
<td>PB17</td>
<td>Mid- and large-sized monocultural producers of crops</td>
<td>Land renters who come from out of the region to crop potatoes, for two or three years; they clear the forest, adapt the land to the agricultural system, and leave it prepared for other crops or for pastures</td>
<td>1</td>
</tr>
<tr>
<td>PB24</td>
<td>Household farming in rural area</td>
<td>Low-scale agricultural activities to produce corn and beans, vegetables, and fruit trees that are intended to be consumed at home</td>
<td>5</td>
</tr>
<tr>
<td>PB29</td>
<td>Small and middle cattle breeders who have diversified livelihood portfolios</td>
<td>Land areas between 1 and 35 ha, with a dedication to other livestock activities; poultry householding, fish householding, pork, raising of heifers, and beef cattle</td>
<td>6</td>
</tr>
<tr>
<td>PB30</td>
<td>Big cattle breeders with diversified livelihood activities</td>
<td>Land areas greater than 35 ha, with a dedication to other livestock activities; poultry householding, fish householding, pork raising, raising of heifers, and beef cattle</td>
<td>1</td>
</tr>
<tr>
<td>PB31</td>
<td>Nonfarm livelihood activities</td>
<td>Land area smaller than 10 ha; income from economic activities not related to the agricultural sector: commerce and workers in the public or private sector</td>
<td>5</td>
</tr>
<tr>
<td>PB32</td>
<td>Land leasing</td>
<td>Owners who derive their income indirectly from agricultural activities, mainly by leasing land for livestock or agriculture</td>
<td>4</td>
</tr>
</tbody>
</table>

### TABLE 3. Resilience levels with their respective definitions and limits.

<table>
<thead>
<tr>
<th>Resilience levels</th>
<th>Definition</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low resilience</td>
<td>The agroecosystem is not able to continue with productive functions</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Low resilience</td>
<td>The agroecosystem presents difficulties to continue with productive functions</td>
<td>0.21</td>
<td>0.4</td>
</tr>
<tr>
<td>Medium resilience</td>
<td>The agroecosystem can continue to function despite disturbances; however, it is sensitive to changes or disturbances</td>
<td>0.41</td>
<td>0.6</td>
</tr>
<tr>
<td>High resilience</td>
<td>The agroecosystem can continue with the productive functions without difficulty; however, changes in the level of resilience may occur in the face of disturbances with greater impact; however, it will not be highly affected</td>
<td>0.61</td>
<td>0.8</td>
</tr>
<tr>
<td>Very high resilience</td>
<td>The household is not affected by these threats, it does not present significant changes in production; it can continue under the mentioned disturbances and continue to provide ecosystem services</td>
<td>0.81</td>
<td>1</td>
</tr>
</tbody>
</table>
Land leasing (Nonfarm livelihood activities (Big cattle breeders with diversified livelihood activities) Household farming in rural area (Small and middle cattle breeders who have diversified portfolios) Mid- and large-sized monocultural producers of crops (Small-size cattle breeders) Large-size cattle breeders (Mid-sized cattle breeders) Small-scale producers of commercial crops (5% of households) Households farming in rural area (100% of households) Small and middle cattle breeders who have diversified livelihood portfolios (25% of households) Big cattle breeders with diversified livelihood activities (25% of households) Nonfarm livelihood activities (50% of households) Land leasing (25% of households)

TABLE 4. Number of households per resilience level, relative to climate and price change impacts, based on the ARI.

<table>
<thead>
<tr>
<th>Resilience level</th>
<th>Climate change: No. of households</th>
<th>Price change: No. of households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low resilience</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Low resilience</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>Medium resilience</td>
<td>64</td>
<td>65</td>
</tr>
<tr>
<td>High resilience</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Very high resilience</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>

TABLE 5. Distribution of resilience levels in the face of climate change, according to household profile.

<table>
<thead>
<tr>
<th>Household profile</th>
<th>Percentage with low resilience</th>
<th>Percentage with medium resilience</th>
<th>Percentage with high resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-size cattle breeders (n = 48)</td>
<td>17%</td>
<td>60%</td>
<td>23%</td>
</tr>
<tr>
<td>Mid-sized cattle breeders (n = 12)</td>
<td>8%</td>
<td>67%</td>
<td>25%</td>
</tr>
<tr>
<td>Large-size cattle breeders (n = 8)</td>
<td>13%</td>
<td>88%</td>
<td>0%</td>
</tr>
<tr>
<td>Small-scale producers of commercial crops (n = 9)</td>
<td>22%</td>
<td>67%</td>
<td>11%</td>
</tr>
<tr>
<td>Mid- and large-sized monocultural producers of crops (n = 1)</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Household farming in rural area (n = 5)</td>
<td>60%</td>
<td>40%</td>
<td>0%</td>
</tr>
<tr>
<td>Small and middle cattle breeders who have diversified livelihood portfolios (n = 6)</td>
<td>0%</td>
<td>83%</td>
<td>17%</td>
</tr>
<tr>
<td>Big cattle breeders with diversified livelihood activities (n = 1)</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Nonfarm livelihood activities (n = 5)</td>
<td>40%</td>
<td>60%</td>
<td>0%</td>
</tr>
<tr>
<td>Land leasing (n = 4)</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

System vulnerabilities depend on the characteristics of their elements; the most identifiable ones are socioeconomic and natural. Economic and social vulnerabilities are closely related. Therefore, they combine in this model to form the socioeconomic system. Maintaining resilience in agroecosystems is crucial to ensure long-term sustainable ecosystem services and production systems that benefit both locals and communities and contribute to sustainable development goals (Bergamini et al. 2013).

The impact of climate change on agroecosystems can be quantified and determined in future research; determining the degree of disturbance caused by this threat to agroecosystems was beyond the scope of this work. Therefore, it was only possible to assess the impact of the variable of water source availability. In addition, the index should be validated in the field as an ex post evaluation.

The method proposed in this paper for quantifying resilience is general and applicable to any tropical basin. Furthermore, the category and variable weights should be sensitive to the state of the socioeconomic system. This would also imply that they are time invariant. However, the question of whether the weights used in the construction of the ARI are still appropriate over a period of time is an open question left for future research.

5. Conclusions

This work proposes an agroecosystem resilience index with respect to threats, such as climate change and price changes, for both production inputs and final products. The objective of the composite indicator is to report on households’
resilience to different types of shocks. In this sense, ARI can be used to provide evidence that variables were actually resilient to shocks and report on the design of policies and/or strategies aimed at strengthening the capabilities of the social system to cope with changes in the system.

In general, decision-makers, such as territory planners, other stakeholders, and the communities themselves, face the need for assertive interventions that guarantee the maintenance or strengthening of resilience in their territories. For these stakeholders, having information that specifically indicates which attributes should be addressed allows the generation of adaptation, mitigation, and resilience improvement strategies that are differentiated for households and/or areas.

The resilience index allows the identification of components that affect the response of the index the most. The same resilience value can be explained by several combinations of categories and variables. For example, a given resilience value may be explained by variables associated with the natural system category, such as the predominant soil-cover area for some households. For other households, resilience can be explained by variables associated with the socioeconomic category, such as lack of knowledge or access to technology and innovation for adaptation. In the first case, the solutions to strengthen resilience may be aimed at establishing mechanisms to financially support or regulate areas for the conservation of forest cover, whereas in the second case, strategies can be selected within the framework of training or facilitating access to technology for households.

The proposed index was operationalized in a strategic basin in the Colombian Andes. However, the index can be evaluated in other strategic basins with similar characteristics in terms of economic activities. The evaluation of the index requires a certain amount of information. Nevertheless, if there is a very similar basin in terms of socioeconomic characteristics and biophysical components, the results of the index could be extrapolated and used for decision-making. The consolidation of indices presents restrictions depending on the scale at which they operate. Local scales demand more detailed information, as is the case for the ARI that works on a household level. Variables associated with the natural category, such as soil properties and approximate forest connectivity, may present restrictions during incorporation in the index. Information related to soil properties is usually scarce and expensive to acquire for an index such as the ARI. In these cases, using information from large-scale maps can be a solution, but highlighting the limitations in interpreting the index is important using this strategy. Approximate forest connectivity was evaluated based on the presence of forest cover on the property and its distance from other forest cover, as a proxy for connectivity in this work. However, in terms of addressing the ecological viability of these patches, we additionally propose incorporating the size and shape of forest fragments in future applications of the index. Last, variables associated with the productive category also have limitations such as the water demand for activities and the availability of water sources.

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Data availability statement. This article draws upon a database developed and used by the following authors in the cited publications (see references for complete information): Berrouet et al. (2020), Machado et al. (2019), and Villegas-Palacio et al. (2020).

REFERENCES


