

1 **Shortened Title:** Approach to a future scenario with SMAES

2

3 **Estimating the future with the Sustainability assessment methodology to soil-**
4 **associated agricultural experiments**

5

6 Oscar Iván Monsalve Camacho^{1*}, Gerrit Hoogenboom², Andrea Onelia Rodríguez-Roa³,

7

Oscar Gonzalo Castillo-Romero⁴

8

¹ Agricultural Engineering Program, Agricultural Sciences Faculty, Universidad de

9

Ciencias Aplicadas y Ambientales (U.D.C.A), Calle 222 # 55-37, Bogotá, Colombia. E-

10

mail: omonsalve@udca.edu.co

11

^{2,4} Agricultural & Biological Engineering Department and the Institute for Sustainable

12

Food Systems, University of Florida, Gainesville, FL, USA

13

³ Colombian Corporation for Agricultural Research – Agrosavia, Direction of Research and

14

Development / Tibaitatá Research Center, Km 14 Mosquera – Bogotá, Colombia

15

16 **Abstract**

17

18 Agricultural sustainability assessments have gained high importance during the last decades.

19

Different tools have been developed for these assessments such as the Sustainability

20

assessment methodology oriented to soil-associated agricultural experiments (SMAES).

21

SMAES quantifies the current sustainability of the different treatments evaluated in

22

experiments associated with the soil. However, efforts aimed to maintain or increase the crop

23 systems sustainability must be planned and measured in the short, medium, and long-term.
24 In this work, some parameters are added to SMAES to estimate the future sustainability. The
25 first parameter is the construction of climate scenarios (RCP 4.5 and 8.5, model CCSM4,
26 periods 2050-2100) to establish the conditions of change in the future. Second, crop yield is
27 modelled with DSSAT (Decision Support System for Agrotechnology Transfer) using the
28 aforementioned climate scenarios. Third, yield modelling results and SMAES sustainability
29 indexes (IS) from climate scenarios are integrated. As a case of study, the current
30 sustainability (IS-A) of five potato fertilization split treatments were initially estimated:
31 Commercial control (Control), Fertilization recommended by Agrosavia (As), Monthly split
32 fertilization recommended by Agrosavia (AsSplit), AsSplit decreasing the amount of
33 fertilizer by 25% (AsSp25), and AsSplit decreasing the amount of fertilizer by 50%
34 (AsSp50). AsSp50 generated the highest current and future sustainability with IS-A = 0.90,
35 IS-45, and IS-85 = 0.88. Results suggest that integrated fertilization management practices
36 generate a higher potato crop sustainability in the Colombian high Andean, both today and
37 the future.

38

39 **Key words:** SMAES, current sustainability, future sustainability, potato, DSSAT, LCA

40

41 **Introduction**

42

43 One of the most accepted definitions of sustainable development: “the development that
44 meets the present needs without compromising the ability of future generations to meet their
45 own” (WCED, 1987), highlights the importance of development in as present as the future

46 conditions. This is also evidenced in some publications in which it is considered the
47 importance of providing, directly or indirectly, for long-term sustainability (e.g., Altieri and
48 Farrell, 2018; Baush et al., 2014; Campbell et al., 2014; De Luca et al., 2015; De Olde et al.,
49 2016; Kanter et al., 2016; Swart et al., 2004). Despite the importance of current and future
50 sustainable development and tools designed to assess sustainability work current conditions,
51 not much has been done to estimate, model, or simulate the sustainability at long term, i.e.,
52 in the future.

53

54 Monsalve et al. (2023) developed SMAES (sustainability assessment methodology oriented
55 to soil-associated agricultural experiments), an adaptable and quantifiable methodology for
56 the evaluation of sustainability oriented to soil-associated agricultural experiments. In
57 SMAES, the outputs are interpreted through a sustainability index that assembles the
58 environmental, social, and economic information of the experiment (Monsalve et al., 2023).
59 The authors used a tomato mixture of mineral and organic fertilization experiment to evaluate
60 SMAES. They found that the chemical treatment was more sustainable than mixtures. Also
61 reported that “it is possible that if the management of the treatments is maintained over time,
62 in 10 or 20 years, the fertilization treatments including organo-mineral mixtures could show
63 the highest yields.” However, it is impossible to predict for sure what the sustainable will be
64 in future decades (Adhikari et al., 2018), due to the amount of soil and climate variables that
65 interact constantly and whose dynamics produces variations in the plant development. Thus,
66 a considerable number of tools have been developed to simulate changing environmental
67 conditions and estimate how these changes modify vegetative and productive aspects of
68 cultivated plants (IICA, 2015). Decision support systems such as DSSAT (Hoogenboom et
69 al., 2019), AquaCrop (FAO, 2017), APSIM (Keating et al., 2003), and EPIC (Sharpley and

70 Williams, 1990) are based on crop modelling and intended to simulate agro-climatic
71 conditions by estimating plant development and growth under multiple scenarios. The next
72 challenge is to define what are these new conditions to simulate, forcing the options to be
73 reduced in a logical and coherent way. In that sense, predicting the dynamics of a certain
74 system or cropping method in the future needs the construction of climate and soil scenarios.

75

76 Climate change studies are constructed from future climate projections provided by existing
77 global climate models. Selecting models is not simple and usually based on the full range of
78 climatic variables changes, as projected by the total set of climate models available or based
79 on the ability of climate models to simulate the climate in the past or based on the
80 combination of both approaches (Lutz et al., 2016).

81

82 Regarding soils, the situation is more complex, since there are no models that allow
83 predicting with enough accuracy all the physical, chemical, and biological properties that
84 interact in the soil-plant system (Löbmann et al., 2022). The most important advances have
85 been done with carbon and nitrogen (Parton et al., 1994; Godwin and Sing, 1998), followed
86 by phosphorus (Dzotsi et al., 2010) modelling. Using few existent soil models (time historical
87 series) might not be accurate, because as weather, it is advisable to understand how the soil
88 properties dynamics have been in the past (≥ 10 years) to predict with less uncertainty future
89 conditions (e.g., Zhang et al., 2016 and Yang et al., 2013). However, measurements of soil
90 properties in a continuous and regularly way in time and space have not been as common as
91 measurements of climatic variables (Evans et al., 2021), where more and more stations are
92 installed and more models and software are built to measure or estimate these variables in all
93 regions of the world (e.g., NASA POWER - Stackhouse and Kusterer, 2019).

94

95 The objective of this work is to adapt the SMAES methodology to assess future sustainability
96 levels of treatments evaluated in agricultural experiments associated with soil. A case study
97 related to the use of a potato split fertilization experiment is presented.

98

99 **Materials and methods**

100

101 A sequence of activities to measure the current and estimate the future agriculture
102 sustainability were conducted. 1) To build climate change scenarios, 2) to measure the current
103 sustainability of the treatments using SMAES, 3) yield modelling with DSSAT Vr 4.7.5
104 (Hoogenboom et al., 2019), and 4) to estimate the future sustainability using SMAES from
105 modelling results of DSSAT.

106

107 **Climate change scenarios and crop modelling**

108

109 **Construction of climate changes scenarios:**

110 The daily series of precipitation, maximum and minimum temperature for the reference
111 period 1971-2019 from the agrometeorological station of the Tibaitatá research center and
112 the simulations of the CCSM4 of the NCAR institute for the present climate and the future
113 period 2050-2100 under the RCP4.5 and RCP8.5 scenarios, taken from the CMIP5, were
114 used. A downscaling process was performed using the Bias Correction and Statistical
115 Downscaling (BCSD) method. This technique seeks to reduce the difference between the
116 observed values and the simulated values by applying an adjustment factor to the model data.

117 Referenced and projected CO₂ data were obtained from Postdam Institute for Climate Impact
118 Research database for RCP 4.5 (Clarke *et al.*, 2007; Smith y Wigley, 2006; Wise *et al.*, 2009)
119 and RCP 8.5 (Riahi *et al.*, 2007).

120

121 **Crop modelling with DSSAT**: The SUBSTOR-Potato cropping system model (CSM) that
122 belongs to the Decision Support System for Agrotechnology Transfer (DSSAT Vr 4.7.5)
123 library was used (Jones *et al.*, 2003; Hoogenboom *et al.*, 2019). This model was chosen
124 because it has been used and calibrated in different environments, showing good adjustments
125 (Raymundo *et al.*, 2014). It was also used and calibrated in agroecological conditions where
126 an experiment (Bogotá Plateu, Mosquera, Colombia) was carried out for potato crop with
127 “Diacol Capiro” cultivar (Forero and Garzón, 2000). Both Forero and Garzón (2000), and
128 Rojas (2011) found a very good fit (> 90%) between the observed and simulated data.

129

130 To run the models in DSSAT, we used the genetic coefficients and soil profile information,
131 reported by Forero and Garzón (2000) and Ordoñez and Bolivar (2014), respectively. The
132 genetic coefficients were re-adjusted for the experimental conditions using the Generalized
133 Likelihood Uncertainty Estimation Methodology (GLUE), available in DSSAT (Jones *et al.*,
134 2011).

135

136 Yield (Yd) is the main indicator for the modelling process because it is typically associated
137 with the three dimensions of sustainability, so its variation will affect many environmental,
138 social, and economic indicators. In DSSAT, yield is driven (but not only) on climate
139 variability function (temperature, rainfall, radiation, and CO₂ variations) and the carbon-

140 nitrogen dynamics, through the soil organic matter modelling with the CENTURY model
141 (Parton et al., 1994), included in DSSAT.

142

143 To define the fit between the observed and simulated yield data, the correlation (r) and the
144 Root Mean Squared Error (RMSE) coefficients (Smith et al., 1997) were used.

145

146 **Current and future sustainability assessment**

147

148 **SMAES summary**: Figure 1 shows a scheme that synthesizes the process of assessing the
149 current (IS-A) and future (IS-45 and IS-85) sustainability indices through SMAES (Monsalve
150 et al., 2023).

151

152 SMAES is divided into three macro-processes (Figure 1). 1) Experiment development
153 (tillage, fertilization, irrigation, or rotation) during which the assessment of soil, plant, and
154 climate variables are conducted as raw indicators, and the production system inventory (PSI)
155 is constructed individually for each Experimental Unit (EU). 2) The entire data set (variables
156 or raw indicators) is divided according to its dimension (environmental, social, or economic)
157 and attribute. In addition, climate variables are processed to build climate scenarios.
158 Subsequently, each indicator is parameterized by defining thresholds (whether there is an
159 optimum; if so, this optimum is the maximum or minimum value in the dataset). Then, a
160 correlation, variance, and comparison analysis were performed to define the benchmark
161 indicators, which are normalized. Finally, each base indicator goes through the selection
162 criteria method (Monsalve et al., 2022) to define the core indicators and the minimum

179 the MIS for the future scenarios. SMAES was run with the new core indicators to calculate
180 the future sustainability of the treatments evaluated. In this way, the agricultural
181 sustainability indexes were obtained under the current (IS-A) and future (IS-45 and IS-85)
182 conditions for all treatments.

183

184 **Case study for models calibration and the sustainability assessment:** A potato split
185 fertilization experiment was carried out on the Tibaitata Research Center, Agrosavia, in
186 Mosquera, Colombia. Potato seeds (*Solanum tuberosum*) from the Diacol capiro variety were
187 planted. A randomized complete block design with five treatments and 20 experimental units
188 (EU) (four repetitions per treatment) was established.

189

190 Five treatments were evaluated: 1) commercial control (Control), fertilization usually done
191 by farmers in terms of fertilizer type, amount, and splits (two splits); 2) fertilization
192 recommended by Agrosavia research centre (As), in terms of fertilizer type, amount, and
193 splits (two splits); 3) monthly split fertilization recommended by Agrosavia (AsSplit) (five
194 splits); 4) AsSplit reducing the amount of fertilizer by 25% (AsSp25) and 5) AsSplit reducing
195 the amount of fertilizer by 50% (AsSp50). Detailed experimental characteristics can be found
196 in Monsalve et al. (2020a).

197

198 SMAES requires the construction of one PSI for each EU. With the PSI, some environmental
199 and social indicators and all economic indicators used in SMAES are estimated. In the PSI,
200 all agricultural exploitation and resource consumption data (inputs, labors, and outputs) were
201 collected (Monsalve et al., 2023).

202

203 **Indicators - variables management**: Table 1 shows all raw indicators evaluated in the
 204 experiment. In total, 42 raw indicators were measured or estimated: 31 environmental, 8
 205 socials, and 11 economics.

206

207 Table 2 shows characteristics of the core (selected) indicators for analysis with SMAES. To
 208 define the core indicators, the selection method included in SMAES was used (Monsalve and
 209 Henao, 2022) to divide the indicators according to their hierarchy (raw, baseline, and core
 210 indicators). The MIS is defined according with the compliance of the different types of
 211 criteria (mandatory, main, alternative non-mandatory, and correlation) and the score obtained
 212 through a checklist. Indicators in the MIS represent each attribute and dimension in SMAES
 213 (Monsalve et al., 2023).

214

215 For all environmental indicators estimated through life cycle assessment (LCA), all resource
 216 consumption and emissions referred to as a functional unit of mass of one kilogram of fresh
 217 commercial potatoes. Extraction of the raw material to the farm gate was the limit of the
 218 system, i.e., an LCA from cradle to door. It was considered a single subsystem, fertilization.
 219 The background processes included the production of fertilizers, where the data for their
 220 production were obtained from the Ecoinvent V3.4 database (Ecoinvent Center, 2017).

221

222 Table 1. Raw environmental, social, and economic indicators evaluated. Methodologic
 223 specifications of core indicators selected are in Table 2.

Raw indicator	Abbreviation	Unit
Environmental		
Soil organic carbon	SOC	%
Carbon stock	StockC	Mg ha ⁻¹
pH	pH	Dimensionless
Electrical conductivity	CE	dS m ⁻¹

Effective cationic exchange capacity	CICE	cmol _(c) kg ⁻¹
Phosphorus	P	mg kg ⁻¹
Exchangeables bases (K ⁺ , Ca ²⁺ , Mg ²⁺ , Na ⁺)	ExBs	cmol _(c) kg ⁻¹
Micronutrients (Fe, Cu, Mn, Zn, B)	McNt	mg kg ⁻¹
Bulk density	Db	g cm ⁻³
Available water capacity	AWC	%
Water retention curve (0.01, 0.03, 0.1, 0.3, and 1.5 MPa)	WRC	%
Water content	WC	cm
Texture	Txt	DL
Aggregate stability	AGG	%
Weighted mean diameter of soil peds	WMD	mm
Geometric mean diameter of soil peds	GMD	mm
Nutrient concentration in plant tissue	Ntr-Veg	mg kg ⁻¹
NO ₃ ⁻ concentration of soil solution	NO3	mg L ⁻¹
Soil management assessment framework	SQ _{SMAF}	Dimensionless
Soil quality indicator using principal component analysis	SQ _{PCA}	Dimensionless
Soil quality simple additive indicator	SQ _{SA}	Dimensionless
Soil quality weighted additive indicator	SQ _W	Dimensionless
Land use	LU	m ² kg ⁻¹
Amount of water per kilogram produced	W-kg	L kg ⁻¹
Amount of nitrogen per kilogram produced	N-kg	g kg ⁻¹
Fresh water toxicity	FWT	kg 1.4-DB eq
Marine water toxicity	MWT	kg 1.4-DB eq
Potential eutrophication	PE	kg PO ₄ ³⁻ eq
Potential acidification	PA	kg SO ₂ eq
Global warming potential	GWP	kg CO ₂ eq
Ozone depletion	OLD	kg CFC-11 eq
Social		
Yield	Yd	kg
Percentage of first category	FCat	%
Wages per cycle per hectare	JC	Unit
Wages per year per hectare	JA	Unit
Work Effort Indicator	ELB	%
High and maximum work effort	EL _{B4,5}	%
Formation of photochemical oxidants	PO	kg C ₂ H ₄ eq
Human Toxicity	HT	kg 1.4-DB eq
Economic		
Variable costs	VC	\$ ha ⁻¹
Fixed Costs	FC	\$ ha ⁻¹
Investment	IV	\$ ha ⁻¹
Gross income	GI	\$ ha ⁻¹

Net Income	NI	\$ ha ⁻¹
Net Present Value	NPV	\$
Benefit-cost ratio	B/C	\$
Opportunity rate obtained	ORO	%
Internal rate of return	IRR	%
Breakeven point by quantity	BPQ	kg ha ⁻¹
Breakeven point by price	BPP	\$ kg ⁻¹

224

225 The social indicators of each attribute were obtained from the PSI, based on a business model
 226 where all the technical, administrative, and management processes followed the Colombian
 227 legal framework (CCB, 2023; DIAN, 2023). All the variable costs such as plant material,
 228 fertilizers, crop protection, wages, and fixed costs such as leasing, public services, salaries,
 229 administration, associated with the production were accounted for and included in the study.
 230 The analysis was carried out based on the technique of investment projects assessment
 231 (Karibskii, 2003a y b), assuming that the production is constant for a cropping area of one
 232 hectare in each EU (project), transforming the values of each variable of the EU area to one
 233 hectare.

234

235 Table 2. Core indicators of the minimum indicators set (MIS), selected in the environmental,
 236 social, and economic dimensions. Thrs = Threshold, HVB = highest value is the best, and
 237 LVB = lowest value is the best.

238

Indicator	Thrs	Method
Environmental dimension		
Attribute Soil quality		
SQ _{PCA}	HVB	$SQ_{PCA} = \prod_{c=1}^{c=n} S_c^{W_c}$ <p style="text-align: right;">Equation 1</p> <p>Where, S_c = Normalized value of the soil property (c), W_c = Weight of c. Detailed calculation is shown in Monsalve et al. (2021)</p>
Attribute Soil-plant		

$$N - kg = \frac{g N m^{-2}}{kgP m^{-2}} \quad \text{Equation 2}$$

N-kg LVB

Where, gN = nitrogen mass in grames; kgP = harvested product mass in kilogrames

Attribute Soil water

NO₃ LVB Measured by installing a suction lysimeter at a 90 cm depth. NO₃⁻ content from leached was measured. Weekly samples were taken throughout the production cycle.

Attribute Soil-atmosphere

$$GWP = \sum_i \left(\frac{\int_0^T a_i c_i(t) dt}{\int_0^T a_{CO_2} c_{CO_2}(t) dt} \right) m_i \quad \text{Equation 3}$$

GWP LVB

Where: T = time (years); a_i = heating produced by the increase in the concentration of a gas i (W m⁻² kg⁻¹); c_i(t) = concentration of the gas i in time (t) (kg m⁻³) and m_i = mass of the substance i (kg). The corresponding CO₂ values are included in the denominator (Heijungs et al., 2012). It was estimated by LCA.

Social dimension

Attribute Food security

FCat HVB Amount of first category harvested product

Attribute Employment generation

JC LVB Day's pay per cycle per hectare

Attribute Human health

EL_B LVB In concordance with the methodology of Monsalve and Luque, 2020b

Economic dimension

Attribute Expenses

VC LVB Sum of variable costs

Attribute Investment

IV LVB All costs associated with the initial economic investment, prior to field activities

Attribute Incomes

$$NI = GI - (VC + FC) \quad \text{Equation 4}$$

NI HVB

Where: GI = Gross incomes; VC = Variable costs; FC = Fixed costs

Attribute Profitability

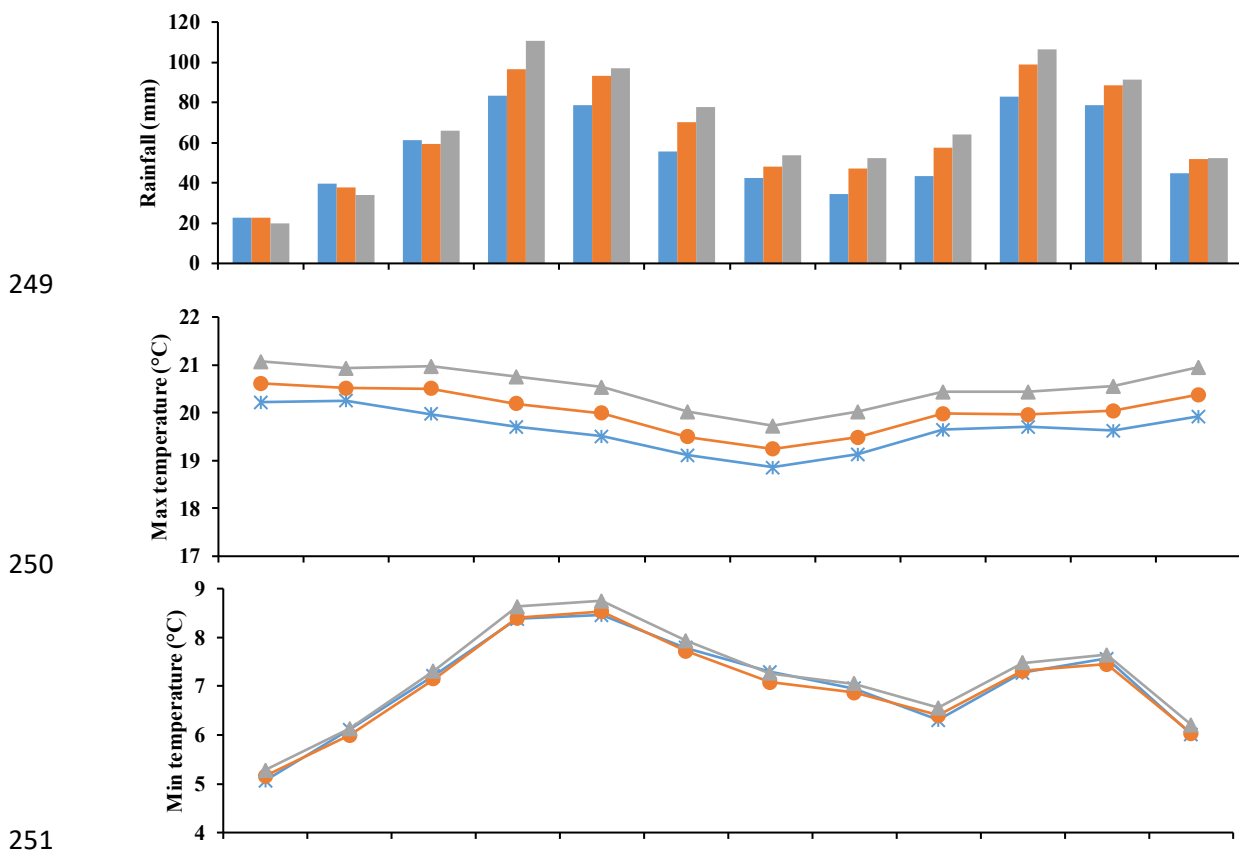
B/C HVB Equation 5

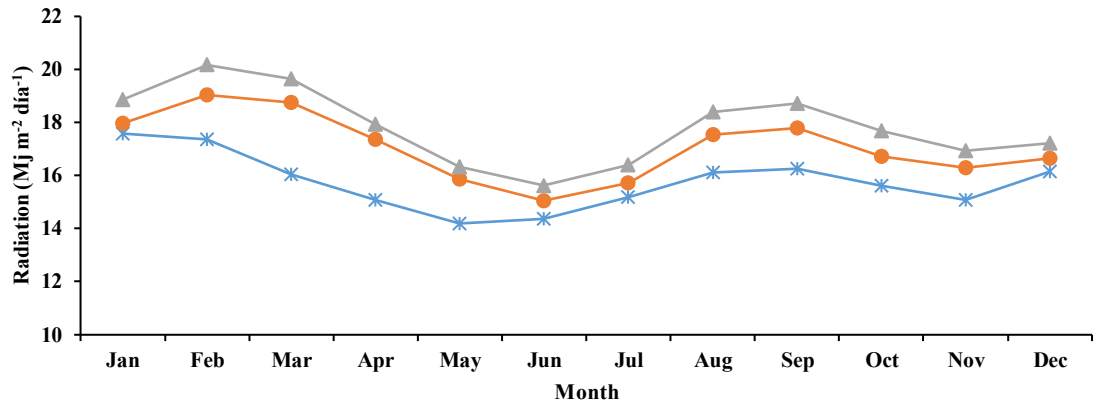
240 Results

241

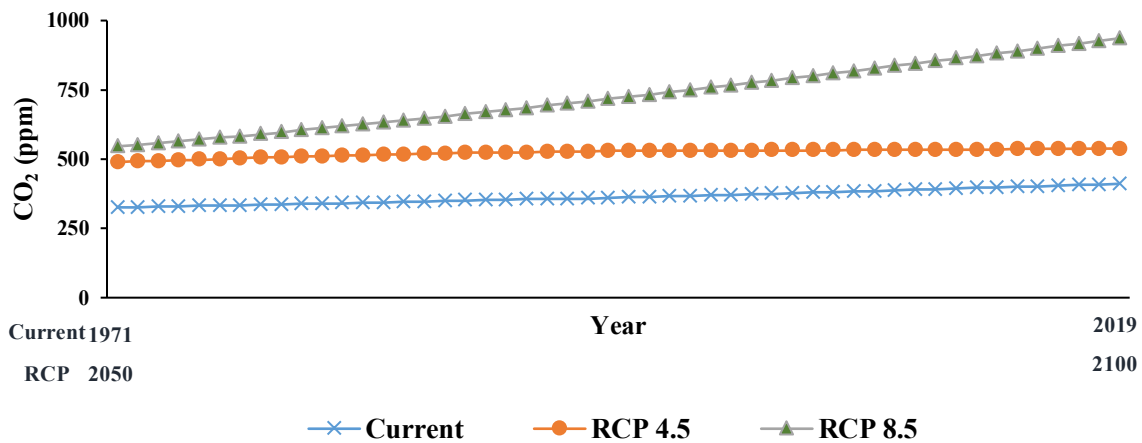
242 Estimating future conditions

243 Climate change scenarios for the 2019 - 2100 period show that rainfall in the study area is
 244 expected to increase on average 13% and 19% for RCP scenarios 4.5 and 8.5, respectively
 245 with respect to the reference period (1971 - 2019) (Figure 2). Maximum temperature is
 246 projected to warm by about 0.4 and 0.9 °C for RCP 4.5 and 8.5, respectively. The minimum
 247 projected temperature should not show significant variations, whereas the radiation is
 248 expected to increase 1.3 and 2.1 $\text{Mj m}^2 \text{ day}^{-1}$ for RCP 4.5 and 8.5, respectively (Figure 2).





252

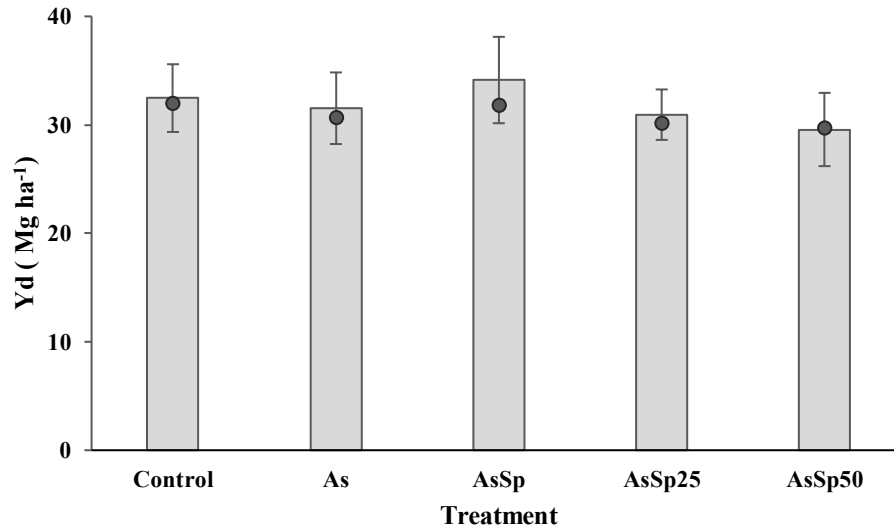


253

254 Figure 2. Annual cycle (average of daily data) of rainfall, maximum and minimum
 255 temperature, radiation, and CO₂ change over time. Current based on reference period (1971
 256 - 2019). RCP 4.5, and 8.5 based on projected period from 2050 to 2100) in the municipality
 257 of Mosquera, Cundinamarca (Colombia).
 258

259 For the yield (Yd) indicator (Table 1), as seen in Figure 3, a highly significant adjustment
 260 between the observed data (bars) and those simulated by DSSAT (points) was shown with r
 261 = 0.89 and RMSE = 3.06, which is consistent with that was found by Forero and Garzón
 262 (2000) and Rojas (2011).
 263

263



264

265 Figure 3. Results observed (bars) and simulated by DSSAT (point) for the yield indicator
 266 (Yd).

267

268 Once the model was calibrated (Figure 3), the simulations were carried out with the climate

269 change scenarios RCP 4.5 and RCP 8.5. To know the variation in Yd over time and define

270 the soil and climate variables that most significantly influence that variation, the soil and

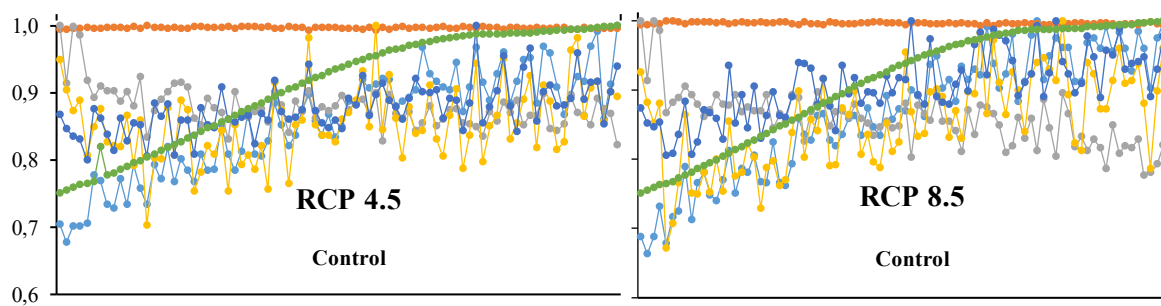
271 climate variables modelled by DSSAT were studied, finding that the trends are similar for all

272 treatments and scenarios evaluated. For all treatments with the RCP 8.5 scenario, organic

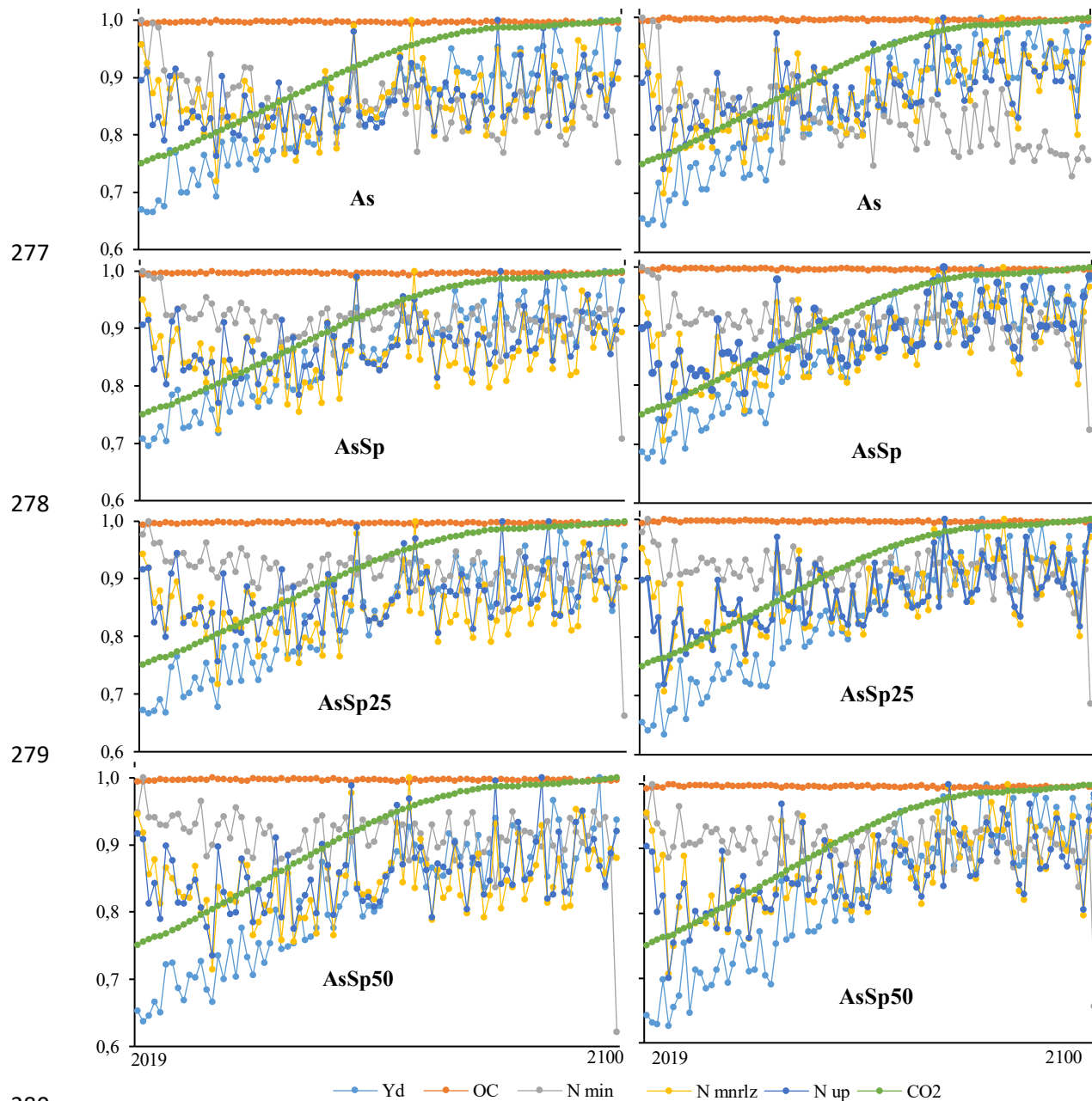
273 carbon (OC) content tends to remain stable over time and that of mineral nitrogen (N min)

274 decreases in response to the increase in nitrogen uptake by plants (N up), stimulated by the

275 Yd increase (Figure 4).



276



280
 281 Figure 4. DSSAT projected results. Standardized Yield (Yd), organic carbon (OC), mineral
 282 nitrogen (N Min), net nitrogen mineralization (N mnrلز), nitrogen uptake (N up), maximum
 283 temperature (T max) and CO₂ variation over time (2019 - 2100) for the RCP 4.5 and RCP
 284 8.5 scenarios.

285

286 A considerable increase in atmospheric CO₂ concentration is expected (Figure 4). This
 287 increase has a highly significant relationship with the increase of Yd. However, differences
 288 in Yd between RCP 4.5 and RCP 8.5 are not as significant compared with differences in CO₂

289 concentration between RCP 4.5 and 8.5, with an average increase of 36 and 74%,
290 respectively, with respect to the reference period (Data not shown).

291

292 **MIS selection**

293

294 Results of indicators selection process are not shown following the methodology of Monsalve
295 et al. (2022). In summary, results are similar for all scenarios evaluated (Current, RCP 4.5
296 and RCP 8.5). In the environmental dimension, there are very highly significant correlations
297 between all indicators of the soil-water and soil-atmosphere attributes. In the soil-plant
298 attribute, a very highly significant correlation can be seen between S-Pr and W-kg indicators
299 since both land use and water consumption are related to production. Namely, how much
300 land area and water is required to produce a kilogram of potatoes. In this experiment, all
301 plots, regardless of the treatment applied, had the same area and the same amount of applied
302 water. The N-kg indicator did not correlate with the other indicators of this attribute. Unlike
303 S-Pr and W-kg, different N amounts were applied between treatments, which suggests that
304 the increase in production was not related to the amount of N applied.

305

306 For the social dimension, the most highly significant correlations are presented between JC
307 and JA for the employment generation attribute and between EL_B y $EL_{B(4,5)}$ for human health.
308 There is no correlation between Yd and FCat, which indicates that the increase in production
309 does not always generate an increase in quality.

310

311 Analysis of variance and comparison of indicators showed many similarities between the
 312 three scenarios, as well as with the correlation. In the current scenario, the soil quality
 313 indicator SQ_W was the only indicator that did not present significant differences. The same
 314 occurred for the W-kg, Yd, and JC indicators in the RCP4.5 and RCP8.5 scenarios.

315

316 According to the score obtained from the selection criteria, SQ_{PCA} (soil quality attribute), N-
 317 kg (soil-plant attribute), NO₃⁻ (soil-water attribute), and GWP (soil-atmosphere attribute)
 318 were defined as core indicators for the environmental dimension with a score of 0.91, 0.78,
 319 0.79, and 0.73, respectively. For RCP scenarios 4.5 and 8.5, eutrophication (EP) indicator
 320 was chosen for soil-water attribute (Table 3).

321

322 Table 3. Indicator selection process for the current (2016), RCP 4.5 and RCP 8.5 scenarios.
 323 W_k = weighter, Ind = Indicator, TSc = Total score, and RCP = Representative concentration
 324 pathway. Highlighted indicators correspond to core indicators.

Attribute	Ind.	Current		RCP4.5		RCP8.5	
		TSc	W _k	TSc	W _k	TSc	W _k
Environmental dimension							
Soil quality	SQ _{SMAF}	0.81		0.81		0.81	
	SQ _{SA}	0.79	0.22	0.79	0.18	0.79	0.18
	SQ _W	0.00		0.79		0.79	
	SQ _{PCA}	0.91		0.91		0.91	
Soil-plant	LU	0.68		0.72		0.72	
	W-kg	0.00	0.26	0.00	0.27	0.00	0.27
	N-kg	0.78		0.78		0.78	
Soil-water	FWT	0.00		0.00		0.00	
	MWT	0.00	0.27	0.00	0.27	0.00	0.27
	EP	0.71		0.75		0.75	
	NO ₃	0.79		---		---	
Soil-atmosphere	AP	0.00		0.00		0.00	
	GWP	0.73	0.26	0.73	0.27	0.73	0.27
	OLD	0.00		0.00		0.00	
Social dimension							
Food security	Yd	0.77		0.00		0.00	
	FCat	0.79	0.33	0.79	0.50	0.79	0.50
Employment generation	JC	0.68	0.35	0.00	---	0.00	---

Human health	EL_B	0.67		0.54		0.54	
	EL_{B(4,5)}	0.00	0.32	0.67	0.50	0.67	0.50
	PO	0.00		0.00		0.00	
	HT	0.67		0.71		0.71	
Economic dimension							
Expenses	VC	0.77	0.25	0.77	0.25	0.77	0.25
	FC	0.64		0.64		0.64	
Investment	IV	0.64	0.21	0.64	0.21	0.64	0.21
Incomes	GI	0.00		0.00		0.67	
	NI	0.81	0.27	0.81	0.27	0.00	0.27
Profitability	B/C	0.77		0.77		0.77	
	NPV	0.00		0.00		0.00	
	ORO	0.00		0.00		0.00	
	IRR	0.69	0.27	0.69	0.27	0.69	0.27
	BPQ	0.75		0.75		0.75	
	BPP	0.65		0.61		0.65	

325

326 For the social dimension, the following indicators were chosen: FCat (food security
327 attribute), JC (employment generation attribute) and EL_B (human health attribute) with 0.79,
328 0.68, and 0.67 points, respectively. For the RCP scenarios 4.5 and 8.5, the indicator FCat was
329 chosen as result of no significant differences in Yd. The employment generation attribute did
330 not have representation because its only indicator (JC) did not show significant differences.
331 In these scenarios, HT was chosen to represent the human health attribute because of the
332 highest score (0.71) (Table 3).

333

334 Regarding the economic dimension, the following were chosen as core indicators: VC
335 (expenses attribute), IV (investment attribute), NI (income attribute) and B/C (profitability
336 attribute) with 0.77, 0.64, 0.82, and 0.77 points, respectively (Table 3).

337

338 **Estimation of sustainability indices (IS)**

339

340 **Treatments comparison:** In the environmental dimension, the AsSp50 treatment generated
 341 the highest soil quality under current and future conditions. AsSp can generate a better soil
 342 production ratio (S-Pr) and a better use of water (W-kg) in the three scenarios. This is because
 343 to its higher production per unit area (Yd). However, AsSp ranked third in terms of amount
 344 of nitrogen consumed per kilogram produced (N-kg). Although AsSp provided the fertilizers
 345 in a split way, it is necessary a higher amount of N compare with AsSp50, which used N
 346 more efficiently with respect to the amount of potato harvested. This treatment (AsSp50)
 347 showed the best results for the other indicators evaluated in the environmental dimension,
 348 being the one that would generate the least negative environmental impact on water and the
 349 atmosphere (Table 4).

350

351 Table 4. Evaluation of indicators for each dimension and treatment in current, RCP 4.5, and
 352 RCP 8.5 scenarios. Equal letters indicate no significant differences between treatments
 353 (Tuckey P <0.05); n = 15. ID = Indicator. Units of indicators are the same as in Table 1.

Attribute	ID	Control			As			AsSp			AsSp25			AsSp50							
		Current	4.5	8.5	Current	4.5	8.5	Current	4.5	8.5	Current	4.5	8.5	Current	4.5	8.5					
Environmental dimension																					
Soil quality	SQ _{SMAF}	0,9	b	0,9	0,9	b	1,0	a	1,0	1,0	a	0,9	b	0,9	0,9	b	1,0	a	1,0	1,0	a
	SQ _{SA}	0,4	b	0,4	0,4	b	0,4	ab	0,4	0,4	ab	0,5	a	0,5	0,5	a	0,5	a	0,5	0,5	a
	SQ _{WP}	0,7	a	0,7	0,7	b	0,7	a	0,7	0,7	ab	0,7	a	0,7	0,7	ab	0,7	a	0,7	0,7	a
	SQ _{PCA}	0,8	d	0,8	0,8	d	0,8	cd	0,8	0,8	cd	0,8	bc	0,8	0,8	bc	0,8	ab	0,8	0,8	ab
Soil – plant	LU	0,3	ab	0,3	0,2	ab	0,3	ab	0,3	0,3	ab	0,3	a	0,2	0,2	a	0,3	ab	0,3	0,3	ab
	W-kg	109	ab	88	85	a	113	ab	91	88	a	103	a	85	82	a	115	ab	92	89	a
	N-kg	9,1	d	7,3	7,1	d	4,8	c	3,9	3,7	c	4,4	bc	3,6	3,5	bc	3,7	b	2,9	2,8	b
Soil – water	FWT	0,0	d	0,0	0,0	d	0,0	c	0,0	0,0	c	0,0	c	0,0	0,0	c	0,0	b	0,0	0,0	b
	MWT	154	d	124	120	d	77	c	62	60	c	71	c	58	56	c	59	b	47	46	b
	EP	0,0	d	0,0	0,0	d	0,0	c	0,0	0,0	c	0,0	bc	0,0	0,0	bc	0,0	b	0,0	0,0	b
	NO ₃	17,2	e				14,4	d				11,0	c				8,2	b			
Soil – Atmosphere	AP	0,0	d	0,0	0,0	d	0,0	c	0,0	0,0	c	0,0	bc	0,0	0,0	bc	0,0	b	0,0	0,0	b
	GWP	0,8	d	0,7	0,7	d	0,4	c	0,3	0,3	c	0,4	bc	0,3	0,3	bc	0,3	b	0,2	0,2	b
	OLD	0,0	d	0,0	0,0	d	0,0	c	0,0	0,0	c	0,0	bc	0,0	0,0	bc	0,0	b	0,0	0,0	b
Social dimension																					
Food security	Yd	33	ab	40	42	a	32	ab	39	40	a	34	a	42	43	a	31	ab	39	40	a
	FCat	0,7	c	0,7	0,7	c	0,7	bc	0,7	0,7	bc	0,8	ab	0,8	0,8	ab	0,8	a	0,8	0,8	a
Employment Generation	JC	98	ab	112	114	a	97	a	110	112	a	105	b	118	120	a	99	ab	112	115	a
	EL _B	3,0	a	3,0	3,0	a	3,0	b	3,0	3,0	a	3,0	e	3,0	3,0	b	3,0	d	3,0	3,0	b

Human health	EL _{B(4,5)}	0,1 a	0,1	0,1 a	0,1 b	0,1	0,1 b	0,1 e	0,1	0,1 e	0,1 d	0,1	0,1 d	0,1 c	0,1	0,1 c	
	PO	0,0 d	0,0	0,2 d	0,0 c	0,0	0,1 c	0,0 bc	0,0	0,1 bc	0,0 b	0,0	0,1 b	0,0 a	0,0	0,1 a	
	HT	0,3 d	0,2	0,0 d	0,1 c	0,1	0,0 c	0,1 bc	0,1	0,0 bc	0,1 b	0,1	0,0 b	0,1 a	0,1	0,0 a	
Economic dimension																	
Expenses	VC	20 d	21	21 d	16 c	18	18 c	17 c	19	19 c	15 b	16	17 b	13 a	15	15 a	
	FC	20 b	20	20 b	19 a	19	19 a	19 a	19	19 a	19 a	19	19 a	19 a	19	19 a	
Investment	IV	13 b	13	13 b	10 a	10	10 a	10 a	10	10 a	10 a	10	10 a	10 a	10	10 a	
Incomes	GI	70 ab	87	90 ab	69 ab	86	89 ab	78 a	95	98 a	71 ab	89	92 ab	66 b	82	85 b	
	NI	31 b	46	49 a	34 ab	49	51 a	42 a	57	60 a	37 ab	53	56 a	34 ab	49	51 a	
Profitability	B/C	1,8 b	2,1	2,2 b	1,9 ab	2,3	2,4 ab	2,1 a	2,5	2,6 a	2,1 a	2,5	2,5 a	2,0 a	2,4	2,5 a	
	NPV	54 b	83	88 b	61 ab	89	94 ab	76 a	105	110 a	67 ab	98	103 ab	61 ab	89	93 ab	
	ORO	0,4 b	0,5	0,5 b	0,5 ab	0,6	0,6 ab	0,5 a	0,6	0,6 a	0,5 a	0,6	0,6 a	0,5 a	0,6	0,6 a	
	IRR	5 b	8	9 b	8 ab	11	11 ab	9 a	13	13 a	8 a	12	13 a	8 ab	11	11 ab	
	BPQ	56 c	52	51 a	48 b	46	45 b	48 ab	45	45 b	47 ab	45	44 bc	45 a	43	43 c	
	BPP	543 b	452	441 a	500 ab	419	409 ab	468 ab	399	390 b	491 ab	409	399 ab	489 a	409	399 ab	

354

355 With respect to the social dimension, the treatment with the highest Yd was AsSp for the
356 current scenario, followed closely by the Control, As, and AsSp25. The AsSp50 treatment
357 resulted in the lowest Yd. Despite the low yield, the amount of the first category potato (FCat)
358 did not show the same trend than yield, with AsSp25 having the highest percentage for all
359 three scenarios. This corresponds with the correlation matrix that shows that Yd and FCat
360 had a small and negative correlation, i.e., -0.27 (Data not shown). This suggests that higher
361 production is not related to a higher quality. It is worth to clarify that in this experiment tuber
362 quality was only measured in terms of tuber size.

363

364 In the economic dimension, AsSp50 spent less money, both in investment (IV) and in fixed
365 costs (FC) and variables (VC). In contrast, “Control” was the one who invested more money
366 on these items. It should be considered that 22% of the total costs of “Control” was allocated
367 to fertilizers, while AsSp50 spend 8.6% (data not shown), which explains these differences.
368 AsSplit obtained the highest gross (GI) and net (NI) incomes, whose magnitude was enough
369 to offset production costs and generate the best profitability indicators in the three scenarios
370 (Table 4).

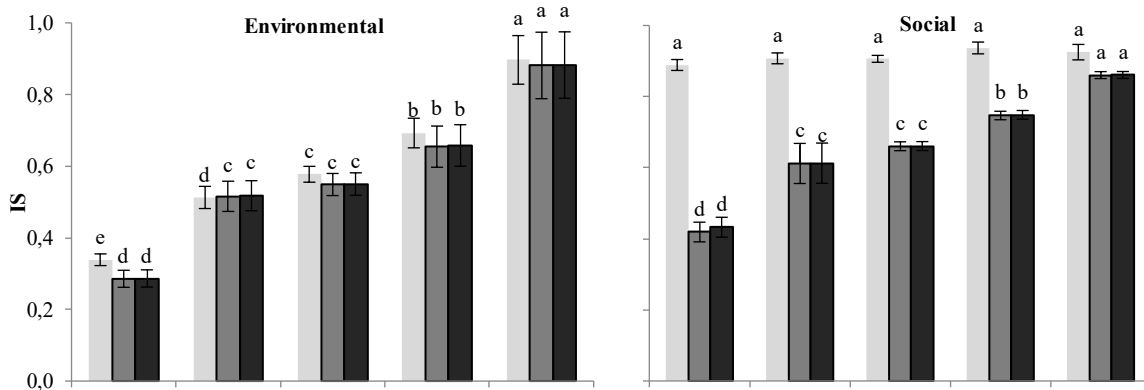
371

372 **Current and future sustainability of the evaluated treatments:** Based on results of the
 373 principal component analysis (PCA) for the environmental dimension, the soil quality
 374 attribute has the lowest weight (W_k) in the three scenarios (Table 3). This is because a single
 375 evaluated indicator (SQ_{PCA}) in this attribute showed highly significant differences between
 376 all treatments (Table 4). A similar situation happened with the social dimension for the
 377 current scenario, where the human health attribute has the lowest W_k . In the social dimension,
 378 the employment generation attribute (W_k) was not assigned for the RCP4.5 and RCP8.5
 379 scenarios because none of its indicators showed significant differences (Table 4). In the
 380 economic dimension, the lowest value of W_k was assigned to the investment attribute (INV)
 381 (Table 3), as it presented significant differences in a single treatment (Control) (Table 4).

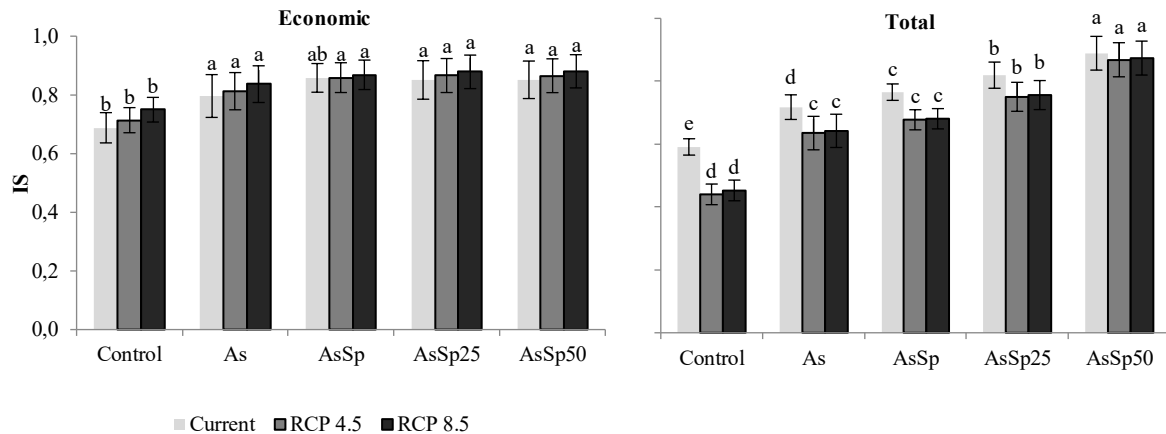
382

383 For the three scenarios, AsSp50 generated the highest environmental and economic
 384 sustainability, while “Control” generated the highest social sustainability (Figure 5). By
 385 comparing the three dimensions, AsSp50 generated the highest sustainability with IS-A =
 386 0.90, IS-45 = 0.88, and IS-85 = 0.88, although this treatment generated the lowest yield (Yd).

387



388



389
390
391
392

Figure 5. Sustainability indexes (IS) between treatments. Same letters indicate no significant differences between treatments (Tukey $P < 0.05$); $n = 15$.

393 Discussion

394

395 Future conditions

396

397 Zhang et al. (2016) and Yang et al. (2013), found that the percentages of C and N will remain
398 constant or even increase in the future (2100) if continuous applications of external organic
399 matter are made. In this experiment, compost was applied in pre-planting, so this suggests
400 that in the future this activity will continue. Although OC content remains constant over time,
401 Yd will tend to increase (Figure 4). In that sense, Bernard et al. (2012), Chen et al. (2018)
402 and Tadasee et al. (2024) found that the effect of the application of organic materials and
403 fertilizers is appreciable mainly in low fertility soils. According to the soil quality indicators,
404 the soil of this study has a high fertility level which is preserved over time. In these
405 conditions, plants have a less response to the differential fertilizers and amendments
406 application. This means that good yields are obtained with few fertilizers. The soil quality

407 indicators evaluated did not vary significantly between treatments, because important soil
408 variations are not expected during seasonal experiments (a single production cycle). On the
409 other hand, it is not easy the assessment of soil quality indicators in the future, because there
410 are no models that simulate many of the properties included in their functions and algorithms.

411

412 The increase in atmospheric CO₂, radiation, precipitation, temperature, and the correct crop
413 water management, generates a high sustainability of the system and therefore there is an
414 increase of crop yield, which maintains nitrogen emissions to air and water at low levels over
415 time. The latter statement makes sense, since increasing atmospheric CO₂ concentration
416 generates higher tubers production (Fleischer et al., 2008 and 2013). However, Raymundo et
417 al. (2017) stated that the SUBSTOR-Potato model underestimates the effect of CO₂ on Yd,
418 which yield estimation is lower than observed. On the other hand, higher values of
419 temperature and radiation tend to generate higher biomass production if an adequate water
420 regime is maintained and the established physiological threshold are not exceeded, especially
421 temperature (Kleinwechter et al., 2016; Lizana et al., 2017). Diacol Capiro potato variety is
422 well-adapted to environments between 2000 and 3500 masl, with average temperatures
423 between 18 and 24 °C (Porras and Herrera, 2015). According to the simulations for future
424 conditions in the studied region, temperature will remain within the appropriate range for
425 crop development, but higher amount of precipitation is expected (Figure 2). These results
426 are consistent with those found by Raymundo et al. (2018), who stated that increases in yield
427 are expected in the coming decades for the mountainous areas of the tropical regions.
428 Although these results contrast with the results found by other authors, who affirm that
429 declines in yields due to climate change are expected (Adavi et al., 2018; Kumar et al., 2015;
430 Sparks et al., 2014; Daccache et al., 2012). Their pessimistic predictions are based on lower

431 water efficiency values when rainfall is reduced, temperature is increased above an optimum
432 threshold, and these models do not include the effect of atmospheric CO₂ on the plant.

433

434 **Sustainability evaluation**

435

436 **Treatments comparison:** In the current scenario, the treatment "Control" showed the best
437 results for employment generation, which in the context of this work means that it required
438 the least number of wages (Table 4). This can be paradoxical considering workers usually
439 prefer more jobs. However, if wages are increased, there will be an effect in production costs.
440 This scenario would make the crop system non-viable, the income would not cover the costs
441 and the sale price would have to be increased. Therefore, this case would negatively impact
442 consumers, many of them with limited economic resources. "Control" also showed the best
443 results in terms of work effort (EL_B and EL_{B(4,5)}) for the three scenarios (Table 4). By
444 applying a fewer type of fertilizers (less mixtures) at a lower frequency (fewer manual
445 applications), "Control" generated fewer activities within this group of indicators compared
446 to the other treatments. However, by applying a higher amount of fertilizers with less splits,
447 "Control" generated the highest impact on human health (PO and HT), while AsSp50 showed
448 the least impact (Table 4). Due to fixation, leaching, and volatilization phenomena, potato
449 fertilization generally has a low efficiency in Colombian high Andean potato crops:
450 phosphorus 10 - 20%, and nitrogen and potassium 30 to 50% (Barrera, 1998, Monsalve et
451 al., 2020a). According to Fedepapa and the Ministry of Environment and Territorial
452 Development of Colombia (2004), the most important item in the list of potato production

453 costs is fertilization (mineral fertilizers, organic fertilizers, and corrective) with 21%,
454 followed by wages (19%), pesticides (14%), and seed (11%).

455

456 Splitting fertilizer applications is conducted to provide the nutrients at the appropriate time
457 and amount, avoiding losses as much as possible. Traditionally, the application of fertilizers
458 for potato in Colombia is made twice during the growing season: pre-planting and hilling or
459 weeding (Guerrero, 1998; Monsalve et al., 2020a). A high amount of fertilizer is supplied
460 each application with a nutrient loss risk due to volatilization or leaching.

461

462 In low-intensity potato productions, the annual release of N-N₂O is 8 kg ha⁻¹, and for higher
463 intensity productions it is 16 kg ha⁻¹, which is higher than for many other crops (Ruser et al.,
464 1998; Monsalve et al., 2020a). By applying a smaller amount of fertilizer and split, N
465 emissions to the environment are reduced (Ning et al., 2023). Burton et al. (2008) found that
466 the potato split fertilization substantially reduced N₂O emissions to the environment,
467 especially during high rainfall, although there was a lower yield and quality of potato tubers
468 (*Solanum phureja*) when fertilization (N, P, K, and Mg) was split in two moments (as
469 traditionally applied in Colombia), compared to the total application of the fertilizer required
470 in pre-planting (Pérez et al., 2008). Likewise, Kuisma (2002) found a higher yield when
471 100% of the N was applied at the time of planting, compared with the split application.
472 Despite this, Añez and Espinosa (2006) found that potato yield was higher with the splitting
473 than treatments of total N and K application. Monsalve et al. (2020a) found that the split
474 fertilization in potato maintains or increase crop yield with less use of fertilizers. Similarly,
475 Battilani et al. (2008) concluded that the split application of N, through fertigation, increases

476 the N efficiency in potato crops. This indicates that there is still no consensus on the adequate
477 amount of fertilizer applications in potato crops.

478

479 **Current and future sustainability**: Sustainability assessments evaluate the interaction of
480 social, environmental, and economic dimensions as a whole, and giving equal importance to
481 each dimension. Each of these dimensions evaluates indicators that are not directly associated
482 with yield. For example, although “Control” had a good yield, it had the lowest percentage
483 of the first category potatoes (FCat) and the highest production costs, ranking last in terms
484 of economic sustainability. Also, by using a higher amount of fertilizer, it generated a bigger
485 environmental impact, while AsSp50, generated the least environmental impact by using a
486 smaller amount of fertilizers (treatment with the lowest yield), which turned out to be the
487 best treatment of the environmental dimension. These results are hopeful that potato is one
488 of the crops with the highest use of fertilizers in the high Andean region in Colombia. Under
489 commercial conditions, doses ranging between 1000 and 2000 kg ha⁻¹ of compound fertilizers
490 applied (Barrera, 1998; Monsalve et al., 2020a). It is necessary to remember two facts: 1)
491 the environmental impact, estimated by LCA, lies its calculations on the production of a
492 kilogram of fresh potatoes and 2) the gross income (GI) comes from the sale of the harvested
493 product. Therefore, more production per unit area (Yd) generates more revenue. This
494 explains why Yd interacts with many environmental, social, and economic indicators.
495 However, it was evidenced that highest yield does not ensure the maximum system
496 sustainability.

497

498 Sustainability assessments by framing the environment, society, and economy, allow seeing
499 globally agricultural production systems. If these analyses were done over time, they would

500 add another dimension to the evaluation by increasing its scope. Even though sustainability
501 is constantly being talked about a long time, the topic has not been deeply studied. This is
502 due to the complexity involved in the modelling process of the soil-plant-atmosphere system
503 (Keestra et al., 2023), which is necessary to predict the dynamics of the crop in the future
504 under different scenarios.

505

506 According to results, two recommendations are proposed for future works: 1) there are
507 biological properties highly susceptible to changes in soil management in the short term and
508 these can be included in soil quality indicators. 2) Crop performance can be simulated in a
509 low soil fertility environment. Moreover, it is relevant to consider that the sustainability
510 assessment in the future has limitations because the modelling process requires calibrated
511 cultivars with the different models. For this case, the potato Diacol Capiro cultivar was
512 calibrated in previous studies.

513

514 **Conclusions**

515

516 Potato yield was modelled under different fertilization treatments and climate change
517 scenarios, where the differences between treatments become less significant in the future,
518 although all treatments tend to generate a higher production. Despite this new outlook, the
519 sustainability results show the same results for present and future, being the treatment with
520 the least amount of fertilizer application (in a split way), the most sustainable over time.
521 Results suggest that integrated fertilization management practices, such as perform and
522 applying the fertilization formula according to soil properties, nutritional requirements, and

523 plant phenology, generates a higher potato crop sustainability in the Colombian high Andean
524 region.

525

526 **CRedit authorship contribution statement**

527

528 **Oscar Iván Monsalve Camacho:** Conceptualization, data curation, formal analysis,
529 methodology, investigation, validation, supervision, funding acquisition, visualization,
530 writing – original draft. **Gerrit Hoogenboom:** Conceptualization, software, validation,
531 supervision, writing – review and editing. **Andrea Onelia Rodríguez-Roa:** Methodology,
532 data curation, visualization, writing – review and editing. **Oscar Gonzalo Castillo-Romero:**
533 Methodology, visualization, writing – review and editing.

534

535 **Declaration of competing interest**

536

537 The authors declared that they have no conflict of interest.

538

539 **Data availability**

540 Data will be made available on request.

541

542 **Acknowledgements**

543

544 The authors thank the Ceiba foundation with its program funded by the Colombian royalty's
545 general system for the state of Cundinamarca. The authors also thank the Ministry of
546 Agriculture and Rural Development of Colombia (MADR) and the Colombian Agricultural
547 Research Corporation (Agrosavia) for financing the project: "Estrategias de producción
548 sostenible de papa en el altiplano Cundiboyacense y Nariño, que permitan la obtención de un
549 producto inocuo y de mínimo impacto".

550

551

552 **Orcid**

553

554 Oscar Iván Monsalve Camacho: <https://orcid.org/0000-0003-2302-805X>

555 Gerrit Hoogenboom: <https://orcid.org/0000-0002-1555-0537>

556 Andrea Onelia Rodríguez-Roa: <https://orcid.org/0000-0001-9279-3607>

557 Oscar Gonzalo Castillo-Romero: <https://orcid.org/0000-0001-8354-2769>

558

559 **References**

560

561 Adavi, Z., Moradi, R., Saeidnejad, A. H., Tadayon, M. R., & Mansouri, H. 2018. Assessment
562 of potato response to climate change and adaptation strategies. *Science Horticulture*, 228,
563 91–102. <https://doi.org/10.1016/j.scienta.2017.10.017>

564 Adhikari, P., Araya, H., Aruna, G., Balamatti, A., Banerjee, S., Baskaran, P., Barah, B. C.,
565 Behera, D., Berhe, T., Boruah, P., Dhar, S., Edwards, S., Fulford, M., Gujja, B., Ibrahim,
566 H., Kabir, H., Kassam, A., Khadka, R. B., Koma, Y.S., Natarajan, U. S., Perez, R., Sen,

- 567 D., Sharif, A., Singh, G., Styger, E., Thakur, A. K., Tiwari, A., Uphoff, N., & Verma, A.
568 2018. System of crop intensification for more productive, resource-conserving, climate-
569 resilient, and sustainable agriculture: experience with diverse crops in varying
570 agroecologies. *International Journal of Agricultural Sustainability*, 16, 1–28.
571 <https://doi.org/10.1080/14735903.2017.1402504>
- 572 Altieri, M.A. 2018. Agroecology. The science of sustainable agriculture, 2nd ed. Taylor &
573 Francis Group, United Kingdom.
- 574 Añez, B., Espinoza, W. 2006. Respuesta de la papa a la aplicación fraccionada de nitrógeno
575 y potasio. *Agricultura Andina*, 11, 28–38.
- 576 Barrera, L. 1998. Fertilización del cultivo de la papa en los departamentos de Cundinamarca
577 y Boyacá. in: Guerrero, R (Ed), Fertilización de cultivos en clima frío. Monómeros
578 Colombo Venezolanos S.A.
- 579 Battilani, A., Plauborg, F. L., Hansen, S., Dolezal, F., Mazurczyk, W., & Bizik, J. 2008.
580 Nitrogen uptake and nitrogen use efficiency of fertigated potatoes. *Acta Horticulturae*,
581 792, 61–67. <https://doi.org/http://dx.doi.org/10.17660/ActaHortic.2008.792.4> 10
- 582 Baush, J.C., Bojórquez, L. T., & Eakin, H. 2014. Agro-environmental sustainability
583 assessment using multicriteria decision analysis and system analysis. *Sustainability*
584 *Science*, 1–17. <https://doi.org/10.1007/s11625-014-0243-y>
- 585 Bernard, E., & Larkin, R. P., Tavantzis, S., Erich, M.S., Alyokhin, A., Sewell, G., Lannan,
586 A., Gross, S.D. 2012. Compost, rapeseed rotation, and biocontrol agents significantly
587 impact soil microbial communities in organic and conventional potato production
588 systems. *Applied Soil Ecology*, 52, 29–41. <https://doi.org/10.1016/j.apsoil.2011.10.002>

- 589 Burton, D. L., Zebarth, B. J., Gillam, K. M., & Macleod, J. A. 2008. Effect of split application
590 of fertilizer nitrogen on N₂O emissions from potatoes. *Canadian Journal of Soil Science*.
591 99, 117–125. <https://doi.org/10.1139/cjss-2018-0150>
- 592 Cámara de Comercio de Bogotá (CCB). Steps to create company. 2023. Available at:
593 <https://www.ccb.org.co/>. Access on: June 25, 2023.
- 594 Campbell, B. M., Thornton, P., Zougmore, R., van Asten, P., & Lipper, L. 2014. Sustainable
595 intensification: What is its role in climate smart agriculture? *Current Opinion of*
596 *Environmental Sustainability*, 8, 39–43. <https://doi.org/10.1016/j.cosust.2014.07.002>
- 597 Chen, Y., Camps-Arbestain, M., Shen, Q., Singh, B., & Cayuela, M. L. 2018. The long-term
598 role of organic amendments in building soil nutrient fertility: a meta-analysis and review.
599 *Nutrient Cycle Agroecosystems*, 111, 103–125. [https://doi.org/10.1007/s10705-017-](https://doi.org/10.1007/s10705-017-9903-5)
600 [9903-5](https://doi.org/10.1007/s10705-017-9903-5)
- 601 Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., & Richels, R. 2007. Scenarios of
602 Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of
603 Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and
604 the Subcommittee on Global Change Research. Department of Energy, Office of
605 Biological & Environmental Research, Washington, 7 DC., USA, 154 pp.
- 606 Daccache, A., Keay, C., Jones, R. J. A., Waterhead, E.K., Stalman, M. A., & Knox, J. W.
607 2012. Climate change and land suitability for potato production in England and Wales:
608 impacts and adaptation. *Journal of Agricultural Science*, 150, 161–177.
609 <https://doi.org/10.1017/S0021859611000839>
- 610 De Luca, A. I., Molari, G., Seddaiu, G., Toscano, A., Bombino, G., Ledda, L., Milani, M., &
611 Vittuari, M. 2015. Multidisciplinary and Innovative Methodologies for Sustainable

- 612 Management in Agricultural Systems: the Mimesmas Project. *Environmental*
613 *Engieneering Management Journal*, 14, 1571–1581.
- 614 De Olde, E., Moller, H., Marchand, F., McDowell, R. W., MacLeod, C. J., Sautier, M.,
615 Halloy, S., Barber, A., Bengue, J., Bockstaller, C., Bokkers, E. A. M., De Boer, I. J. M.,
616 Legun, K. A., Le Quellec, I., Merfield, C., Oudshoorn, F. W., Reid, J., Shader, C.,
617 Szymanski, E., Sorensen, C. A. G., Whitehead, J., & Manhire, J. 2016. When experts
618 disagree: the need to rethink indicator selection for assessing sustainability of agriculture.
619 *Environmental Development and Sustainability*, 1–16. [https://doi.org/10.1007/s10668-](https://doi.org/10.1007/s10668-016-9803-x)
620 [016-9803-x](https://doi.org/10.1007/s10668-016-9803-x)
- 621 Dirección de Impuestos y Aduanas Nacionales (DIAN). Estatuto tributario. 2023. Available
622 at: www.dian.gov.co. Access on: June 25, 2023.
- 623 Dzotsi, K. A., Jones, J. W., Adiku, S. G. K., Naab, J. B., Singh, U., Porter, C. H., & Gijssman,
624 A. J. 2010. Modeling soil and plant phosphorus within DSSAT. *Ecological Modelling*,
625 221, 2839–2849. <https://doi.org/10.1016/j.ecolmodel.2010.08.023>
- 626 Ecoinvent Centre. 2017. Ecoinvent Data V. 2.0. Version 3.4. Swiss centre for life cycle
627 inventories. Available from: <http://www.ecoinvent.org>.
- 628 Evans, D. L., Janes-Bassett, V., Borrelli, P., Chenu, C., Ferreira, C. S.S., Griffiths, R. I.,
629 Kalantari, Z., Keesstra, S., Lal,R., Panagos, P., Robinson, D. A., Seifollahi-Aghmiuni,
630 S., Smith, P., Steenhuis, T. S., Thomas,A., & Visser, S. M. 2022. Sustainable futures over
631 the next decade are rooted in soil science. *European Journal of Soil Science*, 73(1),
632 e13145. <https://doi.org/10.1111/ejss.1314516>
- 633 Federación colombiana de productores de papa (Fedepapa),. Ministerio de Ambiente,
634 Vivienda y Desarrollo Territorial (Minambiente). 2004. Guía ambiental para el cultivo
635 de la papa. Federación Colombiana de Productores de Papa

- 636 Fleisher, D. H., Barnaby, J., Sicher, R., Resop, J. P., Timlin, D. J., & Reddy, V. R. 2013.
637 Effects of elevated CO₂ and cyclic drought on potato under varying radiation regimes.
638 *Agricultural and Forest Meteorology*, 171–172, 270–280.
639 <https://doi.org/10.1016/j.agrformet.2012.12.011>
- 640 Fleisher, D. H., Timlin, D.J., & Reddy, V. R. 2008. Interactive effects of carbon dioxide and
641 water stress on potato canopy growth and development. *Agronomy Journal*, 100, 711–
642 719. <https://doi.org/10.2134/agronj2007.0188>
- 643 Food and Agriculture Organization of the United Nations (FAO). 2017. AquaCrop training
644 handbooks. Book I. Understanding AquaCrop. FAO. P: 59.
- 645 Forero, H. D., & Garzón, M. E. 2000. Validación del modelo de simulación del crecimiento
646 “Substor-potato V. 35” para cuatro variedades mejoradas de papa (*Solanum tuberosum*
647 ssp. andígena) bajo condiciones de cultivo comercial. Tesis de pregrado. Universidad
648 Nacional de Colombia. Facultad de Ciencias Agrarias. Bogotá., Colombia.
649 <https://repository.agrosavia.co/handle/20.500.12324/16894>
- 650 Godwin, D. C., & Singh, U. 1998. Nitrogen balance and crop response to nitrogen in upland
651 and lowland cropping systems, in: Tsuji, G. Y., Hoogenboom, G., Thornton, P. K (Eds),
652 Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht,
653 the Netherlands. p. 55–78. https://doi.org/10.1007/978-94-017-3624-4_4
- 654 Guerrero, R. 1998. Fertilización de cultivos de clima frío. Segunda edición. Monómeros
655 Colombo-Venezolanos, Bogotá. 370 p.
- 656 Heijungs R., & Guinée J. B. 2012. An overview of the life cycle assessment method – past,
657 present, and future. In: Curran M. A (ed), Life Cycle Assessment Handbook. A Guide for
658 Environmentally Sustainable Products. USA: Willey, pp. 15–42.
659 <https://doi.org/10.1002/9781118528372.ch2>

- 660 Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., White,
661 J. W., Asseng, S., Lizaso, J. I., Moreno, L. P., Pavan, W., Ogoshi, R., Hunt, L. A., Tsuji,
662 G. Y., & Jones, J. W. 2019. The DSSAT crop modeling ecosystem. In: Boote, K. J (ed),
663 Advances in Crop Modeling for a Sustainable Agriculture. Burleigh Dodds Science
664 Publishing, Cambridge, United Kingdom. p.173-216.
665 <http://dx.doi.org/10.19103/AS.2019.0061.10>
- 666 Instituto Interamericano de Cooperación para la Agricultura (IICA). 2015. Modelos de
667 simulación y herramientas de modelaje: elementos conceptuales y sistematización de
668 herramientas para apoyar el análisis de impactos de la variabilidad y el cambio climático
669 sobre las actividades agrícolas. IICA.
- 670 Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A.,
671 Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. 2003. The DSSAT cropping
672 system model. *European Journal of Agronomy*, 18, 235–265.
673 [https://doi.org/10.1016/S1161-0301\(02\)00107-7](https://doi.org/10.1016/S1161-0301(02)00107-7)
- 674 Jones, J. W., Jianqiang, H., Boote, K. J., Wilkens, P., Porter, C. H., & Hu, Z. 2011. Estimating
675 DSSAT cropping system cultivar-specific parameters using Bayesian techniques. In:
676 Ahuja, L. R., Liwang, M. (Eds.), *Methods of Introducing System Models into Agricultural*
677 *Research*. American Society of Agronomy, Crop Science Society of America, Soil
678 Science Society of America Madison, WI, USA.
- 679 Kanter, D. R., Musumba, M., Wood, S. L. R., Palm, C., Antle, J., Balvanera, P., Dale, V. H.,
680 Havlik, P., Kline, K. L., Scholes, R. J., Thornton, P., Tittone, P., & Andelman, S. 2016.
681 Evaluating agricultural trade-offs in the age of sustainable development. *Agricultural*
682 *Systems*, 163, 73-88. <https://doi.org/10.1016/j.agsy.2016.09.010>

- 683 Karibskii A. V., Shishorin Y. R. & Yurchenko S. S. 2003a. Financial and economic analysis
684 and efficiency evaluation of investment projects and programs. I. *Automation and Remote*
685 *Control*, 64, 886–904. <https://doi.org/10.1023/a:1024129430374>
- 686 Karibskii A.V., Shishorin Y. R. & Yurchenko S. S. 2003b. Financial and economic analysis
687 and efficiency evaluation of investment projects and programs. II. *Automation and*
688 *Remote Control*, 64, 1205–1224. <https://doi.org/10.1023/a:1025003529815>
- 689 Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth,
690 D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg,
691 K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S.,
692 Chapman, S., McCown, R. L., Freebairn, D. M., & Smith, C. J. 2003. An overview of
693 APSIM, a model designed for farming systems simulation. *European Journal of*
694 *Agronomy*, 18, 267–288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- 695 Keesstra, S. D., Chenu,C., Munkholm, L. J., Cornu, S., Kuikman, P. J.,Thorsøe, M. H.,
696 Besse-Lototskaya, A., & Visser,S. M. 2024. European agricultural soil management:
697 Towards climate-smart and sustainability, knowledge needs and research approaches.
698 *European Journal of Soil Science*,75(1), e13437. <https://doi.org/10.1111/ejss.1343724>
- 699 Kleinwechter, U., Gastelo, M., Ritchie, J., Nelson, G., & Asseng, S. 2016. Simulating cultivar
700 variations in potato yields for contrasting environments. *Agricultural Systems*, 145, 51–
701 63. <https://doi.org/10.1016/j.agsy.2016.02.011>
- 702 Kuisma, P. 2002. Efficiency of split nitrogen fertilization with adjusted irrigation on potato.
703 *Agricultural and food science in Finland*, 11, 59–74. <https://doi.org/10.23986/afsci.5713>
- 704 Kumar, S. N., Govindakrishnan, P. M., Swarooparani, D. N., Nitin, C., Surabhi, J., &
705 Aggarwal, P. K. 2015. Assessment of impact of climate change on potato and potential

- 706 adaptation gains in the Indo-Gangetic Plains of India. *International Journal of Plant*
707 *Production*, 9, 151–170. <https://dx.doi.org/10.5958/2231-3915.2015.00011.5>
- 708 Lizana, X. C., Avila, A., Tolaba, A., & Pablo, J. 2017. Agricultural and Forest Meteorology
709 Field responses of potato to increased temperature during tuber bulking: Projection for
710 climate change scenarios, at high-yield environments of Southern Chile. *Agricultural and*
711 *Forest Meteorology*, 239, 192–201. <https://doi.org/10.1016/j.agrformet.2017.03.012>
- 712 Löbmann, M. T., Maring, L., Prokop, G., Brils, J., Bender, J., Bispo, A., & Helming, K. 2022.
713 Systems knowledge for sustainable soil and land management. *Science of The Total*
714 *Environment*, 822, 153389. <https://doi.org/10.1016/j.scitotenv.2022.153389>
- 715 Lutz, A. F., ter Maat, H. W., Biemans, H., Shrestha, A. B., Wester, P., & Immerzeel, W. W.
716 2016. Selecting representative climate models for climate change impact studies: an
717 advanced envelope-based selection approach. *International Journal of Climatology*, 36,
718 3988–4005. <https://doi.org/10.1002/joc.4608>
- 719 Monsalve, C. O. I., Castillo-Romero, O. G., Bojacá, A. C. R., & Henao, T. M. C. 2023
720 Sustainability assessment methodology oriented to soil-associated agricultural
721 experiments. *Experimental Agriculture*, 59, e18.
722 <https://doi.org/10.1017/S0014479723000145>
- 723 Monsalve, C. O. I., Espitia, E. M., & Bolaños-Benavides, M. M. 2020a. Split fertilization as
724 a strategy reducing the amount of fertilizer applied to potato crops in Colombia. Case
725 of study. *Revista Colombiana de Ciencias Hortícolas*, 14(2), 240-248.
726 <https://doi.org/10.17584/rcch.2020v14i2.10523>
- 727 Monsalve, C. O.I., Gutiérrez- Díaz, J.S., Bojacá-Aldana, C. R., Henao-Toro, M. C., &
728 Espitia-Malagón, E. M. 2021. Soil Quality Indicators with Potential Use at Plot or

- 729 Experimental Unit Scale. *Eurasian Soil Science*, 54 (Suppl 1), S62–S75.
730 <https://doi.org/10.1134/S1064229321140027>
- 731 Monsalve, C. O. I. & Henao, T. M. C. 2022. Selection of the minimum indicator set for
732 agricultural sustainability assessments at the plot scale. *Agronomía Colombiana*, 40(1),
733 98-108. <https://doi.org/10.15446/agron.colomb.v40n1.98797>
- 734 Monsalve, C. O. I., Luque, S. N. Y., & Henao, T. M.C. 2020b. Approach to an indicator to
735 estimate the magnitude of physical effort in crop labors. *Acta Agronómica*, 69(4), 247-
736 255. <https://doi.org/10.15446/acag.v69n4.86501>
- 737 Ning, L., Xu, X., Qiu, S., Lei, Q., Zhang, Y., Luo, J., Ding, W., Zhao, S., He, P., Zhou, W.
738 2023. Balancing potato yield, soil nutrient supply, and nitrous oxide emissions: An
739 analysis of nitrogen application trade-offs. *Science of The Total Environment*, 899,
740 165628. <https://doi.org/10.1016/j.scitotenv.2023.165628>
- 741 Ordoñez, D. N., & Bolivar, G. A. 2014. Levantamiento agrológico del Centro Agropecuario
742 (CAM), 1st ed. Instituto Geográfico Agustín Codazzi (IGAC), Bogotá, Colombia.
- 743 Parton, W., Schimel, D., Ojima, D., & Cole, C. 1994. A general model for soil organic matter
744 dynamics: sensitivity to litter chemistry, texture and management. Pages 147-167 in R.B.
745 Bryant and R.W. Arnold, editors. Quantitative modeling of soil forming processes. SSSA
746 Spec. Publ. 39.
- 747 Pérez, L.C., Rodríguez, L. E., & Gómez, M. I. 2008. Efecto del fraccionamiento de la
748 fertilización con N, P, K y Mg y la aplicación de los micronutrientes B, Mn y Zn en el
749 rendimiento y calidad de papa criolla (*Solanum phureja*) variedad Criolla Colombia.
750 *Agronomía Colombiana*, 26, 477–486.

- 751 Porras, R. P. D., & Herrera, H. C. A. 2015. Modelo productivo de la papa variedad Diacol
752 Capiro para el departamento de Antioquia, 1st ed. Corporación Colombiana de
753 Investigación Agropecuaria (Corpoica), Mosquera, Colombia.
- 754 Raymundo, R., Asseng, S., Cammarano, D., & Quiroz, R. 2014. Field Crops Research Potato,
755 sweet potato and yam models for climate change: A review. *Field Crops Research*, 166,
756 173–185. <https://doi.org/10.1016/j.fcr.2014.06.017>
- 757 Raymundo, R., Asseng, S., Prasad, R., Kleinwechter, U., Concha, J., Condori, B., Bowen,
758 W., Wolf, J., Olesen, J.E., Dong, Q., Zotarelli, L., Gastelo, M., Alva, A., Travasso, M.,
759 Quiroz, R., Arora, V., Graham, W., & Porter, C. 2017. Field Crops Research Performance
760 of the SUBSTOR-potato model across contrasting growing conditions. *Field Crops*
761 *Research*, 202, 57–76. <https://doi.org/10.1016/j.fcr.2016.04.012>
- 762 Raymundo, R., Asseng, S., Robertson, R., Petsakos, A., Hoogenboom, G., Quiroz, R.,
763 Hareau, G., & Wolf, J. 2018. Climate change impact on global potato production.
764 *European Journal of Agronomy*, 100, 87–98. <https://doi.org/10.1016/j.eja.2017.11.008>
- 765 Riahi, K., Gruebler, A., & Nakicenovic, N. 2007. Scenarios of long-term socio-economic and
766 environmental development under climate stabilization. *Technological Forecasting and*
767 *Social Change*, 74, 7, 887-935.
- 768 Rojas, B.E.O. 2011. Evaluación del desarrollo del cultivo de papa bajo escenarios de
769 variabilidad climática interanual y cambio climático, en el sur oeste de la Sabana de
770 Bogotá. Tesis de maestría. Universidad Nacional de Colombia. Facultad de Ciencias.
771 Departamento de Geociencias. <http://www.bdigital.unal.edu.co/5242/>
- 772 Ruser, R., Flessa, H., Schilling, R., Steindl, H., & Beese, F. 1998. Soil compaction and
773 fertilization effects on nitrous oxide and methane fluxes in potato fields. *Soil Science*

- 774 *Society of America Journal*, 62, 1587–1595.
775 <https://doi.org/10.2136/sssaj1998.03615995006200060016x>
- 776 Sharpley, A. N., & Williams, J. R. 1990. EPIC — erosion/productivity impact calculator: 1.
777 Model documentation. U. S. Dep. Agric. Tech. Bull. 1768, 235.
778 <https://www.cabidigitallibrary.org/doi/full/10.5555/19911950112>
- 779 Smith, P., Smith, J.U., Powlson, D. S., McGill, W. B., Arah, J. R. M., Chertov, O. G.,
780 Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L. S., Kelly, R. H., Klein-
781 gunnewiek, H., Komarov, A. S., Li, C., Molina, J. A. E. J., Mueller, T., Parton, W. J.,
782 Thornley, J. H. M., & Whitmore, A. P. 1997. A comparison of the performance of nine
783 soil organic matter models using datasets from seven long-term experiments. *Geoderma*
784 81, 153–225. [https://doi.org/10.1016/S0016-7061\(97\)00087-6](https://doi.org/10.1016/S0016-7061(97)00087-6)
- 785 Sparks, A. H., Forbes, G. A., Hijmans, R. J., & Garrett, K. A. 2014. Climate change may
786 have limited effect on global risk of potato late blight. *Global Change Biology*, 20, 3621–
787 3631. <https://doi.org/10.1111/gcb.12587>
- 788 Stackhouse, P. W., & Kusterer, J. M. 2019. NASA -POWER Data Access Viewer. NASA
789 Langley ASDC User Serv. 1. <https://power.larc.nasa.gov/>
- 790 Swart, R. J., Raskin, P., & Robinson, J. 2004. The problem of the future: Sustainability
791 science and scenario analysis. *Global Environmental Change*, 14, 137–146.
792 <https://doi.org/10.1016/j.gloenvcha.2003.10.002>
- 793 Tadesse, K. A., Lu, Z., Shen, Z., Daba, N. A., Li, J., Alam, M. A., Lisheng, L., Gilbert, N.,
794 Legesse, T. G., Huimin, Z. 2024. Impacts of long-term chemical nitrogen fertilization on
795 soil quality, crop yield, and greenhouse gas emissions: With insights into post-lime
796 application responses. *Science of The Total Environment*, 944, 173827.
797 <https://doi.org/10.1016/j.scitotenv.2024.173827>

- 798 WCED (World Commission on Environment and Development). 1987. Our common future.
799 Oxford University Press
- 800 Wise, M. A., Calvin, K. V., Thomson, A. M., Clarke, L. E., Bond-Lamberty, B., Sands, R.
801 D., Smith, S. J., Janetos, A. C., & Edmonds, J. A. 2009. Implications of Limiting CO₂
802 Concentrations for Land Use and Energy. *Science*, 324, 1183-1186
- 803 Yang, J. M., Yang, J. Y., Dou, S., Yang, X. M., & Hoogenboom, G. 2013. Simulating the
804 effect of long-term fertilization on maize yield and soil C/N dynamics in northeastern
805 China using DSSAT and CENTURY-based soil model. *Nutrient Cycling in*
806 *Agroecosystems*, 95, 287–303. <https://doi.org/10.1007/s10705-013-9563-z>
- 807 Zhang, X., Xu, M., Sun, N., Xiong, W., Huang, S., & Wu, L. 2016. Modelling and predicting
808 crop yield, soil carbon and nitrogen stocks under climate change scenarios with fertiliser
809 management in the North China Plain. *Geoderma*, 265, 176–186.
810 <https://doi.org/10.1016/j.geoderma.2015.11.027>