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11 **Health quality of seed potato and yield losses in Ecuador.**

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28 **Abstract**

29 Low potato productivity in Ecuador is partly attributed to the use of low quality seed tubers. However, seed
30 health quality in Ecuador, and its interaction with altitude and yield has been poorly investigated. We
31 surveyed 11 farmers' fields in Ecuador in 2010 to determine incidence and severity of pathogens and pests
32 affecting foliage and seed tubers, and to determine the influence of altitude and seed sources over seed
33 health quality (pathogen and pest diversity in/on the seed tuber). Additionally, a field experiment was
34 planted in CIP-Quito using assessed seed tubers collected from surveyed farmers' fields, during 2010 and
35 2011, to determine yield responses to seed health quality. Results show that foliage was mainly affected by
36 late blight and flea beetle damages while seed tubers were predominantly affected by black scurf, andean
37 weevil damages, potato virus S and potato virus X. We found that seed health quality was similar among
38 farmers' seed sources, and detected that increase in altitude decreased seed-borne virus diversity. Only
39 seed-borne pathogens and presence of mechanical damages were found to explain yield variation. Seed-
40 borne pathogens affecting yield variation were black scurf on seed tubers, potato virus S, and potato yellow
41 vein virus. However, these factors changed when regressions were performed per seed source or variety.
42 The yield responses to seed health quality of each variety should be considered to fine-tune integrated pest
43 management strategies.

44 **Keywords: Degeneration, Seed borne pests, incidence, virus, yield losses, diversity**

45 Introduction

46 Yield of the potato crop in Ecuador (mean = 7.9 t ha⁻¹; standard deviation [sd]= 1.51; 1993 to 2014) is
47 relatively low in comparison with neighbouring countries like Colombia (18.08 t ha⁻¹) and Peru (14.7 t ha
48 ¹) (FAO 2016). This is caused, in part, by the use of a poor-quality seed (Thiele 1999), especially in terms
49 of seed health (Fankhauser, 2000), as most farmers use seed tubers from informal sources, in which
50 pathogens and pest accumulate over successive cycles of vegetative propagation, reducing yield and
51 quality, in a process called *seed degeneration* (Thomas-Sharma et al. 2015). Viruses have been usually
52 considered the main cause of degeneration, especially Potato Leafroll Virus (PLRV), Potato Virus A
53 (PVA), Potato Virus S (PVS), Potato Virus X (PVX), and Potato Virus Y (PVY) (Salazar L.F. 2003;
54 Scholthof et al. 2011). Other pathogens and pests that cause degeneration include *Rhizoctonia solani*,
55 *Ralstonia solanacearum*, *Pectobacterium* spp., *Globodera* spp., (5) *Meloidogyne* spp., *Tecia solanivora*,
56 among others (Thomas-Sharma et al. 2016).

57 The first report of seed degeneration in Ecuador was done more than a decade ago by Fankhauser (2000).
58 The main results indicated that *R. solani*, *Streptomyces scabies* and *Premnotrypes vorax* were the most
59 important pathogens and pests causing seed degeneration: incidence on tubers reached up to 78% for *R.*
60 *solani*, 28% for *S. scabies*, and 33% for *P. vorax*, and yield reduction was between 17 and 30%. Results
61 also showed low incidence on tubers of PLRV (<3%), PVY (<3%), PVV (<2%), but not for PVX (up to
62 14%) and PVS (up to 96%). PVV reduced yield in single plants from 21% to 41%, but not total yield.

63 Yield losses caused by seed degeneration are highly variable and depend on the agro-ecological conditions,
64 management and host genotype. Losses caused by viruses range from 10 to 90% depending on the virus.
65 For instance, PVY can reduce the yield up to 90% and PVS up to 20% (Salazar L.F. 2003). However, in
66 tropical highland areas where potatoes are grown above 2500 m.a.s.l, such as the Andes, viruses might not
67 reduce the yield as much as in temperate regions, because of the negative correlation between altitude and
68 temperature that decreases vector populations and virus dissemination (Sanchez de Luque et al. 1991;
69 Bertschinger 1992; Fankhauser 2000). In the case of *R. solani* and *S.scabies*, yield losses have been
70 estimated to be about 20 to 30% for *R. solani* (Banville 1989; Fankhauser 2000), and for *S. scabies* no data
71 is available yet. In the case of pests, damages caused by the Andean potato weevil may reduce the price in
72 about 20 to 50% (P. Oyarzún, Gallegos, et al. 2002), and the potato tuber moth complex (*Tecia solanivora*,
73 *Phthorimaea operculella* and *Symmetrischema tangolias* [Dangles et al. 2009]) can cause yield losses of
74 up to 40% and postharvest losses of up to 100% (Palacios et al. 1997). Despite the fact that we have
75 information about the incidence of single pests, poor attention has been given to the multiple pathogens and
76 pests affecting simultaneously the seed tubers.

77 Pathogen and pest incidence, severity and diversity on the tubers depends heavily on the seed source. In
78 developing countries, most of the seed tubers comes from informal seed systems, including farmers' own
79 seed, neighbours or markets (Almekinders C. J. M. et al. 1994; Thiele 1999). In the case of Ecuador, the
80 use of certified seed is increasing, from 3.3% of planted area in 2000 to 4.8% in 2015 (Instituto Nacional
81 de Estadística y Censos 2016), but yields remain low (5.6 t ha⁻¹ in 2000 and 7.3 t ha⁻¹ in 2013) (FAO 2016).
82 Perhaps, this low response of yield to the increased use of certified seed is because of seed quality,
83 especially seed health, that is reduced in any part of the system. As consequence, farmers would not identify
84 the benefits of using certified seed. Virus incidence in tubers coming from the formal system and the

85 informal system in Peru and Ecuador suggest that this hypothesis is true (Bertschinger et al. 1990;
86 Fankhauser 2000).

87 In this study, we report the results of one survey and one field experiment aiming at: (1) determining the
88 incidence and severity of foliage and seed-borne pathogens and pests affecting the potato crop in Ecuador;
89 (2) understanding how altitude and seed sources affect seed health quality; and (3) estimate the effect of
90 seed health on yield. The implications of these results are discussed below.

91 **Materials and Methods**

92 **Incidence and severity of seed borne pests**

93 In 2010, eleven fields owned by small scale farmers of the Consortium of Small Potato Producers
94 (CONPAPA in Spanish) were selected in three provinces of Ecuador (Table 1). The provinces were selected
95 based on the number of hectares of potatoes cultivated, poverty levels, and presence of partner institutions.
96 These were Bolivar, Chimborazo and Tungurahua. Fields were selected depending on the altitude (between
97 2751 and 3634 meters above the sea level, m.a.s.l) (Table 1), planted variety, and farmer's eagerness to
98 collaborate. Field area ranged between 220 and 1776 m², and were planted with any of these six varieties:
99 Chaucha Roja, Dolores, INIAP-Yana Shungo, INIAP-Fripapa, INIAP-Gabriela and Única. In ten fields
100 (Table 1), incidence and severity of foliage diseases and insect damages were assessed in 100 randomly
101 selected plants at flowering by using the keys proposed by Cruickshank et al. (1982) (number of plants per
102 variety: Chaucha Roja = 200, Dolores = 100, INIAP-Fripapa = 200, INIAP-Gabriela = 200, Única = 200,
103 INIAP-Yana Shungo = 100). Farmers were also asked to identify their seed sources. At harvest, farmers
104 selected the best 400 tubers from each of the 11 fields and taken to the facilities of the International Potato
105 Center in Quito (CIP-Quito, 3058 m.a.s.l, 0°22' S, 78°33' W). Tubers were washed, and incidence and
106 severity of pests and diseases were visually assessed as described by James (1971) in each tuber. Physical
107 and physiological issues, such as mechanical damages, misshapen tubers, and immature tubers were also
108 considered. Nematodes were not considered in this survey. Number of tubers assessed per variety were:
109 Chaucha Roja = 1017, Dolores = 400, INIAP-Fripapa = 800, INIAP-Gabriela = 800, Única = 855, INIAP-
110 Yana Shungo = 400.

111 Tubers were then stored in diffuse light, covered with an anti-aphid net, and protected with insecticide
112 (commercial name: Malathion® 50 PM; a.i, malathion, concentration: 500g/kg of product; dose: 5g of
113 product/L) to prevent aphid infestation, until sprouting occurred naturally. A subsample of approximately
114 100 seed tubers was randomly selected out of the 400 seed tubers (selected per field) for virus diagnoses
115 (number of tubers sampled per variety: Chaucha Roja = 404, Dolores = 103, INIAP-Fripapa = 240, INIAP-
116 Gabriela = 237, Única = 286, INIAP-Yana Shungo = 90). To do this, one to 5 sprouts (2 to 3 cm long) of
117 each tuber were collected depending on the availability and variety sprouting time (e.g., Chaucha Roja was
118 collected at 29 days after farmers' fields were harvested, while Única 110 days after harvest). Then, sprouts
119 were disinfested (3% solution of Captan [i.a., Captan, dose; 1.5g/L idem]) and planted in trays in a net
120 house at CIP-Quito, until having plants 8 to 10 cm tall. Plants were then transplanted into 3-kg pots and
121 protected with an anti-aphid net until they were 15 to 20 cm tall. Leaf samples from top, middle and bottom

122 of the plant were then taken and pooled together. Tubers used for virus diagnosis were put back into diffuse
123 light storage until new sprouts appeared, and were used in the yield loss experiment described below.

124 DAS-ELISA and NASH (Nucleic Acid Spot Hybridization) were performed for virus diagnosis using
125 materials provided by the Virology Unit at CIP in Lima, Peru. DAS-ELISA was carried out according to
126 the protocol proposed by CIP (2007) to detect the following viruses : Andean Potato Latent Virus (APLV),
127 Andean Potato Mottle Virus (APMoV), PLRV, PVA, PVS, PVX, PVY. After completing DAS-ELISA,
128 positive samples were determined by visual observation when samples turned yellow. Positive and negative
129 controls were obtained from the National Agricultural Research Institute (acronym in Spanish INIAP)
130 laboratory of Biotechnology and the BIOREBA company.

131 NASH was performed to detect Potato Yellow Vein Virus (PYVV) according to the protocols for Potato
132 spindle tuber viroid proposed by CIP (1993a) and CIP (1993b). The samples were prepared in the facilities
133 of CIP-Quito and then sent to the to the facilities of CIP in Lima for virus detection. To prepare the samples,
134 briefly, nitrocellulose membranes were soaked in distilled water, washed twice with SSC 20X, and dried at
135 ambient air. Then, leaf samples were macerated with two volumes of extraction buffer (49.4 ml of
136 Formaldehyde (37%) + 50.6 ml of SSC 10X). These extracts were transferred to Eppendorf tubes and
137 centrifugated at 12000 rpm per 5 minutes. After centrifugation, an aliquot of 3-4 μL of the supernatant was
138 transferred to the membranes and dried at ambient air. Finally, membranes were baked at 80 °C for two
139 hours.

140 Incidence was calculated as the percentage of plants with positive reaction in DAS-ELISA/nitrocellulose
141 membranes in relation to the total number of plants.

142 **Yield losses caused by seed borne pests**

143 A field experiment was carried out by planting a random subsample of 1360 seed tubers (experimental unit
144 = one seed tuber) coming from the previous experiment (therefore pest incidence and severity and virus
145 presence was known for each tuber) to estimate yield loss as a response of seed health, from October 2010
146 until December 2011 at CIP-Quito (average temperature 12.3°C and average accumulated rainfall per
147 month 175 mm). Seed tubers were planted when sprouts were 1 to 2-cm long. Tubers from the same variety-
148 field combination were planted together in 75-m² plots, which were randomly allocated in a 2325-m² plot.
149 The fallow area between each 75-m² plot was 2.7 m. Planting was done at 0.4 m between plants and 1.2 m
150 between rows. Certified seed tubers (G4; [Salazar 1995]) of INIAP-Fripapa were planted between
151 experimental units to avoid cross contamination. Plants were then labelled individually. Agronomic
152 practices were done following local recommendations (P. Oyarzún, Gallegos, et al. 2002; P. Oyarzún,
153 Chamorro, et al. 2002). Plants were harvested individually when reached full maturity (130 to 180 days
154 after planting, depending on the variety) and yield was measured (g plant⁻¹).

155 **Statistical analysis**

156 Analysis of incidence and severity of foliage and seed borne pests were performed using descriptive
157 statistics. Incidence data of seed borne pests were used to calculate the Shannon index, which provided an
158 estimate of pathogen and pest diversity as a function of variety, seed source and altitude. It was calculated

159 as described by Kosman (1996) and Perez et al. (2001) as follows $Hs = -\sum_j (p_j \times \ln(p_j))$, $j = 1 \dots n_p$,
160 where p_j is the frequency of the i th seed borne pest and pathogen, and n_p is the number of seed borne pests
161 and pathogens identified. An additional Shannon index was calculated only including viruses. Using the
162 program “R” (version 3.3.2), a multiple linear regression was performed (command *lm*) to estimate the
163 effect of seed health (pest and pathogen incidence and severity) of seed borne pests on yield loss.
164 Assumptions of linearity were assessed by the default diagnostic plots of the program and the variance
165 inflation factor (Car package, command *vif*) (Faraway 2016; Fox et al. 2016).
166 In order to deal with multicollinearity, a general regression model adjusting by the effects of the varieties
167 was performed, and then the most meaningful parameters were selected. With these parameters, regressions
168 were performed aggregating by seed source and variety. Raw data collected during the survey and field
169 experiments (including weather data for the field experiment) was deposited in the CIP Dataverse
170 Repository: <http://dx.doi.org/10.21223/P3/XVAGXC> (Navarrete et al. 2016)

171 **Results**

172 During our survey, we identified three seed sources: (1) Self provided, (2) market, and (3) formal system
173 (Table 1). The varieties Chaucha Roja, Dolores, INIAP-Gabriela and Única were self-provided by the
174 farmers. Chaucha Roja from one farmer’s field was the only variety acquired in the market, and INIAP –
175 Fripapa and INIAP- Yana Shungo (Table 1) were obtained from the formal system.

176 **Incidence and severity of foliage diseases, insect pests and seed borne pests**

177 We identified 5 foliage diseases and 8 pests (Table 2). Diseases found were: black leg (*Pectobacterium*
178 sp.), common rust of potato (*Puccinia pitteriana*), early blight (*Alternaria solani*), late blight (*Phytophthora*
179 *infestans*), and stem canker (*Rhizoctonia solani*). Insect damages found were: Andean potato weevil
180 (*Premnotrypes vorax*), aphids (several species involved such as *Macrosiphum* sp. or *Myzus* sp.), leafminer
181 (*Liriomyza* spp.), potato flea beetle (*Epitrix* spp.), thrips (*Frankliniella tuberosi*), white grub (*Barotheus*
182 sp), white fly (*Bemisia* sp. or *Trialeurodes vaporariorum*), and wireworm (*Agriotes* sp.). From this list, the
183 most predominant diseases were late blight and common rust of potato. Average incidence of late blight
184 was 65.9% and severity 15%. The lowest incidence was in variety INIAP-Yana Shungo (2%) and the
185 highest was in Dolores (97%; Table 2). The second most prevalent disease was common rust of potato with
186 an average incidence of 17% and severity of 1.3%. Varieties showing the lowest incidence were Chaucha
187 roja and INIAP-Yana Shungo (0%); while the highest was found on the variety INIAP-Fripapa (49%;Table
188 2).

189 Potato flea beetle and thrips were predominantly found during the survey (Table 2). The average incidence
190 of the potato flea beetle was 39.2% and the severity 5.7% with the lowest incidence found on INIAP-
191 Fripapa (1.5%) and the highest on Única (99%). Average incidence of thrips was 37.9%. We did not find
192 thrips on the plants of INIAP-Yana Shungo, but these were found on 87% of plants of the variety Dolores.
193 We found 19 seed borne pests and three physical and physiological blemishes (Table 3). Diseases found on
194 the seed tubers were: black leg (*Pectobacterium* sp.), black scurf (*Rhizoctonia solani*), fusarium dry rot
195 (*Fusarium* sp.), silver scurf (*Helminthosporium* sp.), powdery scab (*Spongospora subterranea*), and

196 cracking, i.e., term used to describe symptoms caused by *R. solani* (elephant hide), *Streptomyces* spp. and
197 other cracking like symptoms. Insect damage was caused by the Andean potato weevil (*Premnotrypes*
198 *vorax*), potato flea beetle (*Epitrix* sp.), potato tuber moth complex (*Tecia solanivora*, *Symmetrischema*
199 *tangolias*, or *Phthorimaea operculella*), white grub (*Barotheus* spp.), and wireworm (*Agriotes* spp.). The
200 most prevalent diseases were black scurf and cracking (Table 3). Average incidence of black scurf was
201 80.5% and severity was 3.2%. The lowest incidence of black scurf was in variety INIAP-Yana Shungo
202 (42%) and the highest was in Única (95.8%). Cracking was the second most important problem affecting
203 seed health quality. Average incidence was 18.3% and average severity was 0.6%. Chaucha Roja was the
204 least affected variety (1.5% incidence) while INIAP-Gabriela was the most affected (37.3%).
205 Andean weevil and white grub damages were also important (Table 3). Average incidence of the damage
206 of Andean weevil was 46.4% with a severity of 4.7%. The least affected variety was Única (1.5% incidence)
207 and the most affected was Dolores (82.5%). Damage caused by white grubs was found in 8.3% of tubers
208 with a severity of 0.6% (Table 3). The least affected variety was INIAP-Fripapa (1% of incidence) and the
209 most affected variety was INIAP-Yana Shungo (16.5%). Tubers with symptoms of tuber blight (*P.*
210 *infestans*) were not found in this study.
211 Virus diagnosis revealed that 38.0% of the tubers sampled were free of virus, 45.1% were infected with one
212 virus, 16.3% were infected with two viruses, and 0.01% were infected with three viruses. Virus infection
213 with more than three viruses was not found on the sample. Viruses with the highest incidence were PVS
214 (46.2%) and PVX (43.8%) (Table 3). PVS was not found on INIAP-Fripapa, but in all the tubers of Dolores
215 (Table 3). Similarly, PVX was not found on INIAP-Yana Shungo, but it was found in all the tubers of
216 Chaucha Roja. Incidences of PVA and APMoV were low (0.8 and 1%, respectively; Table 3). These two
217 viruses were found only in the variety INIAP-Gabriela in 5% and 6% of the tubers, respectively. PVX and
218 PVS were present simultaneously in 11% of the tubers. Other simultaneous viral infections were low
219 (incidence < 2%), these were: APLV+PLRV=0.7%, APLV+PVS=1.7%, APLV+PVX=1%,
220 APLV+PVY=0.4%, APMoV+PVA=0.8%, APMoV+PVS=0.2%, APMoV+PVX=0.1%,
221 APMoV+PYVV=0.1%, PLRV+PVX=0.8%, PVA+PVX=0.2%, PVS+PVY=0.4%, PVS+PYVV=0.5%,
222 PVX+PVY=0.4%, PVX+PYVV=0.5, PYV+PYVV=0.2%. PVX+PVY+PVS=0.001%,
223 PVX+PVS+PYVV<0.001%, PVX+PVS+APLV<0.001%, PVX+PLRV+APLV<0.001%,
224 PVX+APMoV+PVA<0.001%, PVY+PVS+APLV=0.001%.

225 Three physical and physiological blemishes were found during this survey: mechanical damages,
226 misshapen tubers, and immature tubers. Interestingly, almost half of the tubers sampled were found to be
227 immature (47.2%). The lowest incidence of immature tubers was found on the variety INIAP-Fripapa (0.8%),
228 while the highest was found on the variety INIAP-Yana Shungo (99.5%). A small portion of misshapen
229 tubers were found during this sampling (3%, Table 3). All the tubers of the variety INIAP-Gabriela had the
230 variety's tuber shape at harvest, while 20.8% of the tubers of the variety Única were misshapen.

231 **Seed borne pest and pathogen diversity**

232 Pest and pathogen diversity on the seed tubers was assessed using the Shannon diversity index where a
233 larger index indicates a larger diversity. Taking into account all pests and diseases, the Shannon diversity
234 indexes were the following: Dolores: 1.12 ($n = 103$ tubers); INIAP-Fripapa: 1.62 ($n = 240$); Chaucha Roja:

235 1.94 ($n = 404$); INIAP-Yana Shungo: 2.18 ($n = 90$); Única: 2.39 ($n = 286$); and INIAP-Gabriela: 2.71 ($n =$
236 237). The Shannon diversity index for all the pests did not show any relationship with the altitude. However,
237 we found a negative correlation with altitude when the Shannon diversity index was calculated for viruses
238 only (Figure 1A). The coefficient of determination (R^2) indicated that the altitude explained 6% of the
239 variability of the Shannon diversity index when including all varieties (Figure 1A, dashed line), and 22%
240 when excluding INIAP-Gabriela (Figure 1A, full line). Considering all the pests and pathogens, we found
241 no differences in the Shannon diversity index among tubers harvested from different seed sources ($p > 0.05$)
242 (Figure 1B): tubers produced with seed from the formal system had a Shannon diversity index of 1.7 (sd =
243 0.5; $n = 330$ tubers); tubers coming from seed from the market: 1.67 (sd = 0.6; $n = 360$); and tubers coming
244 from seed which was self-provided by the farmer: 1.82 (sd = 0.6; $n = 670$).

245 **Yield losses caused by seed borne pests**

246 Average yield during the field experiment was 1010.5 g plant⁻¹ (sd= 785.8) and, as expected, there were
247 large differences among varieties: Chaucha Roja: 437.1 g plant⁻¹ (sd = 298.4); Dolores: 595.8 g plant⁻¹ (sd
248 = 252.7); INIAP-Fripapa 1150.1 g plant⁻¹ (sd = 417.9); INIAP-Gabriela: 2262.8 g plant⁻¹ (sd = 717.1);
249 INIAP-Yana Shungo: 883.8 g plant⁻¹ (sd = 515.8); and Única: 734.9 g plant⁻¹ (sd= 454.7).

250 Before describing the models obtained in this section, it is worth to note that the factor of varieties was
251 considered important driving yield variation. It was able to explain 65% of the variability in yield, but it
252 was excluded from the analysis due to problems of multicollinearity.

253 The multiple linear regression identified ($n = 1103$ observations) four significant parameters interacting
254 with the varieties studied: presence or absence of PVS, PVYV and mechanical damage, and severity (%)
255 of black scurf on the seed tuber (Table 4). Multiple regressions aggregated depending on the seed source
256 were different. The multiple linear regression for the seed that was self-provided by the farmer had an R^2
257 (coefficient of determination) of 40%, and predicted an average yield of 1739.2. It detected the presence
258 and absence of PVS and PVYV as important factors explaining yield variability. PVS had a negative
259 influence over the yield explaining 38% of the variability while the presence or absence of PVYV has a
260 positive influence on yield explaining 2% of the variability (Table 4). The model estimated for the varieties
261 acquired in the market showed a lower R^2 of 7% with an average yield of 375.3 g plant⁻¹. It identified the
262 severity of black scurf as the only important factor affecting positively yield (Table 4). The regression for
263 the seed that was acquired from the formal system had an R^2 of 7% and estimated an average yield of 1181.6
264 g plant⁻¹. The model identified two significant parameters that had a negative influence on yield, presence
265 and absence of PVS and mechanical damage (Table 4).

266 Regressions were different among varieties which R^2 ranged from 8 to 11% (Table 4). For Chaucha Roja,
267 the model ($R^2 = 8\%$) found the presence and absence of PVS and severity of black scurf as significant
268 predictors affecting yield. PVS had a negative influence on yield while severity of black scurf had a positive
269 influence on yield. For INIAP-Fripapa ($R^2 = 9\%$), the regression identified only the presence or absence of
270 mechanical damage as significant parameters for yield variation. For INIAP-Gabriela ($R^2 = 14\%$), three
271 predictors were detected: presence or absence of PVS, presence or absence of PVYV, and severity of black
272 scurf. PVS had a negative effect on yield variation while black scurf and PVYV had a positive effect on
273 yield variation. For variety INIAP-Yana Shungo ($R^2 = 11\%$), the model identifies the presence or absence

274 of mechanical damage as the only predictor of yield variability. For Unica ($R^2 = 11\%$), the regression
275 detected two predictors: presence or absence of PVS and severity (%) of black scurf. PVS had a negative
276 effect on yield variation while black scurf had a positive effect on yield variation. The model for variety
277 Dolores was not estimated since the contribution of the parameters to the variation in yield was not
278 significant.

279 **Discussion**

280 Main findings of this study were the following: (1) in the foliage, the most important pests were late blight
281 and potato flea beetle (Table 2), while in the tubers the most important were black scurf and Andean potato
282 weevil; viruses with the highest incidences were PVS and PVX; (2) altitude had a negative effect on virus
283 diversity and explained between 6 and 22% of its variability; pest diversity was similar in tubers harvested
284 from different seed sources; (3) models estimating yield responses were different when aggregated by seed
285 source or varieties. Due to the fact that the survey and the field experiment were performed in a single year
286 (2010-2011) omitting replicates, conclusions from this study have to be taken cautiously.

287 **Incidence and severity of seed borne pests**

288 The most important foliage disease found was late blight. This disease was present in 65.9% of the plants
289 assessed (Table 2), indicating that it is still one of the main biotic factors limiting the productivity in the
290 country as suggested by Hijmans et al. (2000) and P. Oyarzún et al. (2001). Damages of potato flea beetle
291 follow late blight in importance with an incidence 39.2%. Although, we were aware about the importance
292 about this pest, it is the first time that data about damage of potato flea beetle is reported in Ecuador.

293 Black scurf and Andean potato weevil showed the highest incidences on tubers. Black scurf was present in
294 the 80.5% of the tubers sampled, however, low severities were detected (mean = 3.2%, sd = 1.7, Table 3).
295 Fankhauser (2000) reported similar results about incidence of black scurf when sampling tubers of the
296 varieties INIAP-Gabriela and INIAP-Esperanza in the province Chimborazo (78% incidence). Incidence of
297 the Andean potato weevil was also high (46.4%) (Table 3), but approximately 50% less than previously
298 reported by Fankhauser (2000) (88% incidence). These results may indicate that management strategies to
299 control *R. solani* proposed by local organizations are not working, or are not being adopted by farmers since
300 the incidence of black scurf remain stable from 1998 to 2010, when Fankhauser (2000) and our group did
301 the surveys. Our experience suggest a poor adoption of the management strategies by farmers, and points
302 out the need of strengthening local extension services (Parsa et al. 2012). In contrast, incidence of Andean
303 potato weevil has dropped nearly 50%, from 88% in 1998 to 43.9% in 2010, suggesting better adoption of
304 integrated management practices, more efficient insecticides, or other causes (e.g., an unforeseen effect of
305 climate change on the population of *Premnotrypes vorax*).

306 Cracking symptoms were found on the 18.3% of the tubers sampled (Table 3). This high incidence reported
307 might be the result of the use of “cracking” as a generic term to refer to symptoms that could be produced
308 either by *R. solani*, *Streptomyces* spp., or other causes, and suggest the need for a specific study to define
309 the etiology of cracking.

310 Our results confirm that the presence of tuber blight in the country is limited. A previous research found
311 similar incidences of tuber blight on farmer fields in the provinces of Bolívar, Cañar, Carchi, Chimborazo,

312 Pichincha and Tungurahua (P. J. Oyarzún et al. 2005). Probably, the low incidence of tuber blight found is
313 associated with the soil microbiological and physical-chemical characteristics affecting the development of
314 the disease (Carla Garzón and Forbes 1999; Villamarin et al. 2011). In spite of it, special attention should
315 be given to tuber blight since there is evidence of pre-emergence infection caused by *P. infestans* in Ecuador
316 (Kromann et al. 2008).

317 Viruses have been considered the main factors to reduce seed quality. Our results showed that in the
318 provinces of Bolivar, Chimborazo and Tungurahua of Ecuador, the mild viruses PVS and PVX were the
319 most prevalent viral problems, found in 46.2% and 43.8% of the tubers sampled, respectively (Table 3).
320 Surveys performed in Peru during 1985-1987 and in Ecuador in 1998 also found that both of these viruses
321 were predominant in farmers' fields (Bertschinger et al. 1990; Fankhauser 2000). On the contrary, recent
322 research points out to a high incidence of PVY in the varieties INIAP-Fripapa and Superchola (Gomez et
323 al. 2015), but such contrast might be influenced by the seed source. This variation in results stresses out the
324 importance of understanding ecological conditions, on-farm management practices, seed sources and
325 planted variety to determine viral incidence.

326 **Seed borne pest and pathogen diversity**

327 We found that altitude has a negative effect on virus diversity. Our results support the findings of Sanchez
328 de Luque et al. (1991) and Fankhauser (2000) where they report higher incidences of PVX, PVS, PVY,
329 PLRV and PYVV at lower altitudes than at higher altitudes. Our results confirm that there are beneficial
330 effects of the traditional on-farm practice of using seed tubers produced at high altitudes as an strategy to
331 improve seed health (Thiele 1999). However, specific experiments should be considered to confirm these
332 findings, and determine the effect of the seed tubers produced at higher altitudes when planted at lower
333 altitudes or other plots on the productivity and seed health quality.

334 Our results show that, at the time the survey was done, seed health was similar among seed sources (Figure
335 1B). Similar observation were done by Bertschinger et al. (1990) when comparing viral incidence among
336 different seed sources. However, it is expected that seed health quality improves in the next years due to a
337 large governmental investment on seed replacement with certified seed. In any case, our results point out
338 to the weaknesses in the formal seed production system that does not allow farmers to perceive the
339 advantage of using high quality seed. Additionally, these results highlight the importance to fine-tune on-
340 farm seed management practices that promote the increase of seed health quality, and to acquire a better
341 understanding of the seed system and seed sources in Ecuador to support the dissemination of high quality
342 seed to farmers.

343 **Yield losses caused by seed borne pests**

344 As seen in our results, models estimating yield responses were different between seed sources (Table 4).
345 PVS and PYVV explained yield variation when seed was self-provided by farmers, black scurf when seed
346 was acquired from the market, and PVS and mechanical damage when seed was obtained from the formal
347 system. Additionally, the effect of seed health quality per variety over yield responses was different (Table
348 4). For instance, the regression model for Chaucha Roja ($R^2 = 9\%$) identified that the presence of PVS and

349 severity of black scurf in the seed tuber explained yield variation, while for INIAP-Fripapa, only the
350 presence of mechanical damage had an influence (Table 4).

351 Several studies have shown an increase on yield up to 50% when using seed tuber in optimal physiological
352 and health conditions in comparison with farmer seed tubers (Alvarez 1988; Bertschinger et al. 1995;
353 Wissar 1995; Andrade et al. 2008; Gildemacher et al. 2011; Cesar Garzón 2014). However, these studies
354 have ignored the complexity of interactions (synergy and antagonism) between seed-borne pests and
355 pathogens in multiple contexts (e.g. different soils, environments, and host-pest-pathogen interactions).
356 Inconsistencies of our models (Table 4) suggest that current methodological approaches to understand how
357 seed health quality correlates with yield variation in multiple contexts need still to be further improved, and
358 highlight the relevance of understanding interactions between the different varieties and the seed-borne
359 pest/pathogens to establish indicators that define seed health quality. Similar considerations were
360 mentioned by Thomas-Sharma et al. (2016).

361 PVS was consistently identified in our models (Table 4) as one the main drivers for yield decline during
362 the period 2010-2011. Additionally, our models per variety estimate that losses caused by this virus range
363 from 27 to 43%. Losses in yield caused by this virus alone are variable but reports mention that it is able to
364 reduce up to 20% of yield (Manzer et al. 1978; Hooker 1981). Special attention need to be given to this
365 virus since the results of our survey revealed a high level of incidence (Table 3 and Table 4).

366 PYVV was identified as one of the factors explaining a positive effect on yield variation (partial R^2 of the
367 model for seed self-provided =2%; and partial R^2 for the model of INIAP-Gabriela = 4%). In our case, this
368 effect was driven by a single variety, INIAP-Gabriela, in which infected plants (see Incidence of PYVV on
369 Table 3) showed a higher yield (2689.2 g plant⁻¹; sd = 811.5) than healthy plants (2222.5 g plant⁻¹; sd =
370 696.6) (t-test: p-value < 0.01;

371 Figure 2). Salazar (2006) and Guzmán-Barney et al. (2012), on the contrary, indicated that yield is highly
372 reduced in the presence of PYVV and is an emerging disease in Andes. The unusual response of INIAP-
373 Gabriela to PYVV proposes a promising case of investigation to understand this interaction, but also other
374 interactions due to the fact that this variety registered the highest seed-borne pest and pathogen diversity
375 (Figure 1 and Table 3) and the highest yield (Table 4).

376 *R. solani* is able to induce yield losses up to 30% on farmer fields (Banville 1989). However, the influence
377 of this pathogen is remarkably affected by the weather and the on-farm management practices (James and
378 McKenzie 1972; Gudmestad et al. 1979; Hill and Anderson 1989; Atkinson et al. 2010). During our
379 experiment, losses in yield caused by *R. solani* were not detected, although, the model detected this
380 pathogen as an important factor driving increase on yield. It is likely that the lack of enough inoculum
381 density induced an increase on yield since the average severity of black scurf on the seed tuber was 3.23%
382 of black scurf (Table 3). Unfortunately, there is no information supporting these findings.

383 The presence of mechanical damage was relevant in our study (partial R^2 of the model for seed obtained
384 from the formal seed system =2%; and partial R^2 for the model of INIAP-Fripapa and INIAP-Yana Shungo
385 = 9% and 11%). The presence of mechanical damage had a negative influence on the yield for the models
386 of the seed obtained from the formal system and INIAP-Fripapa; while it had a positive influence on the
387 yield for the model of INIAP-Yana Shungo. These contradicting results might be due to the fact that
388 mechanical damages were not characterized and only register as either presence or absence. The

389 development of indicators to quantitatively describe mechanical damages could have helped to better
390 estimate losses in yield caused by mechanical damages present on seed tubers.

391 Despite the fact that our experiment was performed only once without no replicates, our models show that
392 there are several factors affecting yield. We should be cautious at the moment of using this information.
393 Further research is necessary to understand how the seed health quality affects yield taking into account
394 genotype characteristics and different complex conditions (implementing different replicates of the
395 experiment). We believe that resistance to seed borne pathogens should be explore among Ecuadorian
396 varieties to contribute to the improvement of seed health quality in the hands of smallholder farmers.

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403

404 **Author’s contributions**

405 J. Andrade Piedra designed the experiments; I. Navarrete and N. Panchi performed the experiments and
406 analyzed the data; I. Navarrete and J. Andrade-Piedra wrote the article; P. Kromann and G. Forbes provided
407 technical comments and edited the article.

408 **References**

- 409 Almekinders C. J. M., Louwaars N. P., and De Bruijn G. H. 1994. Local seed systems and their importance
410 for an improved seed supply in developing countries. *Euphytica* 78: 207–216.
411 doi:10.1007/BF00027519.
- 412 Alvarez, EDDY V. 1988. Método simple de selección para la producción de semilla de papa. *Revista*
413 *Latinoamericana de la papa* 1: 18–24.
- 414 Andrade, Nancy, Andrés Contreras, and Ingrid Castro. 2008. Evaluación comparativa del efecto en el
415 rendimiento y sanidad en el cultivo de la papa al utilizar semilla certificada y sin certificar. *Agro*
416 *sur* 36: 111–114.
- 417 Atkinson, Dennis, Michael K. Thornton, and Jeffery S. Miller. 2010. Development of *Rhizoctonia solani*
418 on Stems, Stolons and Tubers of Potatoes I. Effect of Inoculum Source. *American Journal of*
419 *Potato Research* 87: 374–381. doi:10.1007/s12230-010-9143-6.
- 420 Banville, G. J. 1989. Yield losses and damage to potato plants caused by *Rhizoctonia solani* Kuhn.
421 *American Potato Journal* 66: 821–834. doi:10.1007/BF02853963.
- 422 Bertschinger, L. 1992. Modelling of potato virus pathosystems by means of quantitative epidemiology: An
423 exemplary case based on virus degeneration studies in Peru. PhD, Zurich, Switzerland: Swiss
424 Federal Institute of Technology.
- 425 Bertschinger, L., U. C. Scheidegger, J. Muñoz, and A. Hidalgo. 1995. Efecto de diferentes virus sobre el
426 rendimiento potencial de la papa y su interacción con el estado de brotamiento de tubérculos-
427 semilla en la costa del Perú. *Rev. Latinoam. Papa* 7: 36–54.
- 428 Bertschinger, L., U. Scheidegger, K. Luther, O. Pinillos, and A. Hidalgo. 1990. La incidencia de virus de
429 papa en cultivares nativos y mejorados en la Sierra Peruana. *Rev. Latinoam. Papa* 3: 62–79.
- 430 CIP. 1993a. Sample Preparation for PSTVd Detection by Nucleic Acid Hybridization. In *Techniques in*
431 *plant virology. CIP Training Manual*, Jayasinghe, U.; Salazar, L. F. Technical Training Unit 2.5.2.
432 Lima, Peru: International Potato Center (CIP).

- 433 CIP. 1993b. Preparation of ³²P-Labeled Probes by RNA Transcription. In *Techniques in plant virology*.
434 *CIP Training Manual*, Jayasinghe, U.; Salazar, L. F. Technical Training Unit 5.2.3. Lima, Peru:
435 International Potato Center (CIP).
- 436 CIP. 2007. *DAS-ELISA Kit for potato virus detection*. International Potato Center. Lima, Peru.
- 437 Cruickshank, G., H. E. Stewart, and R. L. Wastie. 1982. An illustrated assessment key for foliage blight of
438 potatoes. *Potato Research* 25: 213–214. doi:10.1007/BF02359807.
- 439 Dangles, Olivier, Verónica Mesías, Verónica Crespo-Perez, and Jean-François Silvain. 2009. Crop damage
440 increases with pest species diversity: evidence from potato tuber moths in the tropical Andes.
441 *Journal of Applied Ecology* 46: 1115–1121. doi:10.1111/j.1365-2664.2009.01703.x.
- 442 Fankhauser, Corinne. 2000. Seed-transmitted diseases as constraints for potato production in the tropical
443 highlands of Ecuador. Diss., Eidgenössische Technische Hochschule ETH Zürich, Nr. 13770,
444 2000.
- 445 FAO. 2016. FAOSTAT.
- 446 Faraway, Julian J. 2016. Introduction. In *Extending the Linear Model with R: Generalized Linear, Mixed*
447 *Effects and Nonparametric Regression Models, Second Edition*, 1–24. Uk: CRC Press.
- 448 Fox, John, Sanford Weisberg, Daniel Adler, Douglas Bates, Gabriel Baud-Bovy, Steve Ellison, David Firth,
449 et al. 2016. Package “car.”
- 450 Garzón, Carla, and G. Forbes. 1999. Suppression of *P. infestans* in Six Ecuadorian Soils. In *Late Blight: A*
451 *Threat to Global Food Security*, 117. Quito, Ecuador.
- 452 Garzón, Cesar. 2014. Efecto de cuatro categorías de semilla en el rendimiento de papa (*Solanum tuberosum*
453 L.) Variedad Superchola. Ecuador: Escuela Superior Politecnica de Chimborazo.
- 454 Gildemacher, P. R., E. Schulte-Geldermann, D. Borus, P. Demo, P. Kinyae, P. Mundia, and P. C. Struik.
455 2011. Seed potato quality improvement through positive selection by smallholder farmers in
456 Kenya. *Potato Research* 54: 253–266. doi:10.1007/s11540-011-9190-5.
- 457 Gomez, Jonathan, I Navarrete, A Taípe, Jorge Andrade-Piedra, and Peter Kromann. 2015. Cuanto degenera
458 la semilla de papa al reutilizarla en sucesivos ciclos de producción? In. Ibarra, Ecuador.
- 459 Gudmestad, Neil C., Richard T. Zink, and J. E. Hugeliet. 1979. The effect of harvest date and tuber-borne
460 sclerotia on the severity of Rhizoctonia disease of potato. *American Potato Journal* 56: 35–41.
461 doi:10.1007/BF02851121.
- 462 Guzmán-Barney, Mónica, Liliana Franco-Lara, Daniel Rodríguez, Lorena Vargas, and Juan E. Fierro. 2012.
463 Yield losses in *Solanum tuberosum* Group Phureja Cultivar Criolla Colombia in Plants with
464 Symptoms of PVV in Field Trials. *American Journal of Potato Research* 89: 438–447.
465 doi:10.1007/s12230-012-9265-0.
- 466 Hijmans, R. J., G. A. Forbes, and T. S. Walker. 2000. Estimating the global severity of potato late blight
467 with GIS-linked disease forecast models. *Plant Pathology* 49: 697–705. doi:10.1046/j.1365-
468 3059.2000.00511.x.
- 469 Hill, C. B., and N. A. Anderson. 1989. An evaluation of potato disease caused by isolates of *Rhizoctonia*
470 *solani* AG-3. *American Potato Journal* 66: 709–721. doi:10.1007/BF02896827.
- 471 Hooker, W. J. 1981. *Compendium of Potato Diseases*. International Potato Center.
- 472 Instituto Nacional de Estadística y Censos. 2016. Encuesta de Superficie y Producción- Agropecuaria-
473 Continua (BBD). *Instituto Nacional de Estadística y Censos*.
- 474 James, W. C. 1971. An illustrated series of assessment keys for plant diseases, their preparation and usage.
475 *Canadian plant disease survey* 51: 39–65.
- 476 James, W. C., and A. R. McKenzie. 1972. The effect of tuber-borne sclerotia of *Rhizoctonia solani* Kühn
477 on the potato crop. *American Potato Journal* 49: 296–301. doi:10.1007/BF02861667.
- 478 Kosman, E. 1996. Difference and diversity of plant pathogen populations: A new approach for measuring.
479 *Phytopathology* 86.
- 480 Kromann, Peter, Arturo Taípe, Jorge L. Andrade-Piedra, Lisa Munk, and Gregory A. Forbes. 2008.
481 Preemergence Infection of Potato Sprouts by *Phytophthora infestans* in the Highland Tropics of
482 Ecuador doi:10.1094/PDIS-92-4-0569. *Plant Disease* 92: 569–574.
- 483 Manzer, F. E., D. C. Merriam, and P. R. Hepler. 1978. Effects of potato virus S and two strains of potato
484 virus X on yields of Russet Burbank, Kennebec, and Katahdin cultivars in Maine. *American Potato*
485 *Journal* 55: 601–609. doi:10.1007/BF02852178.
- 486 Navarrete, Israel, Nancy Panchi, Peter Kromann, Gregory Forbes, and Jorge Andrade-Piedra. 2016. Dataset
487 for: Health quality of seed potato and yield losses in Ecuador. International Potato Center
488 Dataverse.
- 489 Oyarzún, Pedro, Fernando Chamorro, Juan Córdova, Fausto Merino, Franklin Valverde, and José
490 Velásquez. 2002. Manejo Agronómico. In *El Cultivo de Papa en Ecuador*, 1sted., 111–113.
491 Ecuador.

- 492 Oyarzún, Pedro, Patricio Gallegos, Cesar Asaquibay, Greg Forbes, José Ochoa, Betty Paucar, Marcelo
493 Prado, Jorge Revelo, Stephen Sherwood, and Fausto Yumisaca. 2002. Manejo Integrado de Plagas
494 y Enfermedades. In *El Cultivo de Papa en Ecuador*, 1sted., 111–113. Ecuador.
- 495 Oyarzún, Pedro J., Carla D. Garzón, Diego Leon, Irene Andrade, and Gregory A. Forbes. 2005. Incidence
496 of potato tuber blight in Ecuador. *American Journal of Potato Research* 82: 117–122.
497 doi:10.1007/BF02853648.
- 498 Oyarzún, Pedro, J.A Taipe, and G. A. Forbes. 2001. *Phytophthora infestans* su actividad y particularidades
499 en el Ecuador. Perfil de País. In *Proceedings of the International Workshop Complementing
500 Resistance to Late Blight (Phytophthora Infestans) in the Andes.*, E.N. Fernández-Northcote, 17–
501 27. Cochabamba, Bolivia: International Potato Center.
- 502 Palacios, Maria, Gloria Sotelo, and Edison Saenz. 1997. La polilla de la papa *Tecia solanivora* (Povolny).
503 In *Primer seminario taller internacional sobre manejo integrado de Tecia Solanivora*. Ibarra,
504 Ecuador: INIAP Archivo Historico.
- 505 Parsa, Soroush, Raúl Ccanto, Edgar Olivera, María Scurrah, Jesús Alcázar, and Jay A. Rosenheim. 2012.
506 Explaining Andean Potato Weevils in Relation to Local and Landscape Features: A Facilitated
507 Ecoinformatics Approach. *PLOS ONE* 7: e36533. doi:10.1371/journal.pone.0036533.
- 508 Perez, Willmer G., J. Soledad Gamboa, Yesenia V. Falcon, Mario Coca, Rubi M. Raymundo, and Rebecca
509 J. Nelson. 2001. Genetic structure of Peruvian populations of *Phytophthora infestans*.
510 *Phytopathology* 91: 956–965.
- 511 Salazar, Luis F. 1995. Ecología, epidemiología y control de las enfermedades virales. In *Los virus de la
512 papa y su control*, 177–212. Lima, Peru: International Potato Center.
- 513 Salazar, Luis F. 2006. Emerging and Re-emerging Potato Diseases in the Andes. *Potato Research* 49: 43–
514 47. doi:10.1007/s11540-006-9005-2.
- 515 Salazar L.F. 2003. Potato viruses after the XXth century: effects, dissemination and their control.
- 516 Sanchez de Luque, Concepción, Pedro Corzo, and Octavio Perez. 1991. Incidencia de virus en papa y su
517 efecto sobre rendimiento en tres zonas agroecologicas de colombia. *Revista Latinoamericana de
518 la Papa* 4: 36–51.
- 519 Scholthof, H. B., V. Y. Alvarado, J. C. Vega-Arreguin, J. Ciomperlik, D. Odokonyero, C. Brosseau, M.
520 Jaubert, A. Zamora, and P. Moffett. 2011. Identification of an ARGONAUTE for antiviral RNA
521 silencing in *Nicotiana benthamiana*. *Plant Physiol* 156: 1548–55. 21606315.
522 doi:10.1104/pp.111.178764.
- 523 Thiele, Graham. 1999. Informal potato seed systems in the Andes: Why are they important and what should
524 we do with them? *World development* 27: 83–99.
- 525 Thomas-Sharma, S., A. Abdurahman, S. Ali, J. L. Andrade-Piedra, S. Bao, A. O. Charkowski, D. Crook,
526 et al. 2016. Seed degeneration in potato: the need for an integrated seed health strategy to mitigate
527 the problem in developing countries. *Plant Pathology* 65: 3–16. doi:10.1111/ppa.12439.
- 528 Villamarin, D., G. Orquera, C. Mogroviejo, C. D. Garzón, J. Molineros, G. A. Forbes, A. Koch, and M.
529 Benitez. 2011. Suppressiveness to *Phytophthora infestans* infection in potato tubers by Andean
530 soils from three provinces of Ecuador. *Phytopathology* 101: S183.
- 531 Wissar, Ricardo. 1995. Producción de tubérculos-semillas de papa con pequeños agricultores de la región
532 de Potosí-Bolivia. *Revista Latinoamericana de la Papa* 7: 1.

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Tables and figures

Table 1. Field location, potato varieties and seed sources in a survey conducted in the central highlands of Ecuador in 2010.

Province	Altitude	Latitude	Longitude	Variety	Seed source ¹	Area (m ²)
Bolívar	3596	S 01° 32'52.4"	W 78° 55'14.5"	Dolores	Self-provided	238
	2812	S 01° 38'38.8"	W 78° 58'29.1"	INIAP-Fripapa	Formal system (G3)	803
	2751	S 01° 40'48.3"	W 78° 57'34.1"	Única	Self-provided	1375
	2793	S 01° 40'45.0"	W 78° 57'26.8"	INIAP-Yana Shungo	Formal system (G4)	220
Chimborazo	3576	S 01° 36'31.6"	W 78° 48'21.8"	Chaucha Roja	Market	888
	3566	S 01° 36'33.1"	W 78° 48'22.0"	Chaucha Roja	Market	277
	3455	S 01° 36'28.2"	W 78° 46'49.3"	INIAP-Gabriela	Self-provided	375
	3601	S 01° 38'28.9"	W 78° 47'48.4"	Chaucha Roja	Self-provided	539
	3527	S 01° 34'25.1"	W 78° 46'37.1"	INIAP-Gabriela	Self-provided	757
Tungurahua	3634	S 01° 18'21.4"	W 78° 46'41.1"	INIAP-Fripapa	Formal system (G3)	618
	3035	S 01° 06'26.7"	W 78° 32'00.2"	Única	Self-provided	569

¹The "G" notation refers to the number of successive plantings from in-vitro plants (Salazar 1995b). For the case of Ecuador, the seed G3 corresponds to the category "Registrada" and G4 to the category "Certificada".

Table 2. Incidence and severity of foliage diseases and insect pests in six potato varieties in Ecuador (for the number of observations see *Materials and Methods*)

	Dolores			Chaucha Roja			INIAP-Yana Shungo			INIAP-Fripapa			INIAP-Gabriela			Única			Average			
	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	
	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	s	\bar{X}	s
Diseases																						
Early blight	0.0	.	.	0.0	.	.	12.0	1.0	4.7	0.5	0.01	0.07	3.5	0.2	1.1	14.0	2.2	7.7	5.0	6.4	0.8	1.0
Late blight	97.0	26.5	15.3	95.0	21.7	15.6	2.0	0.1	0.5	90.5	21.1	16.1	20.5	1.0	2.3	90.5	20.0	21.4	65.9	42.8	15.1	11.1
Black leg ¹	0.0	.	.	1.5	.	.	1.0	.	.	0.0	.	.	0.0	.	.	1.0	.	.	0.6	0.7	.	.
Stem canker ¹	4.0	.	.	0.5	.	.	0.0	.	.	1.0	.	.	0.0	.	.	3.0	.	.	1.4	1.7	.	.
Common rust	34.0	1.2	2.4	0.0	0.0	0.0	0.0	0.0	.	49.0	6.2	8.0	1.0	0.0	0.2	18.0	0.3	0.6	17.0	20.7	1.3	2.4
Insect damages																						
White grub ¹	0.0	.	.	7.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	1.2	2.9	.	.
Wireworm ²	18.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	3.0	7.3	.	.
Andean weevil	13.0	1.0	3.3	17.0	2.5	7.3	0.0	.	.	0.5	0.01	0.1	0.0	.	.	1.0	0.1	0.7	5.3	7.7	0.6	1.1
Whitefly ³	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	0.5	.	.	0.1	0.2	.	.
Leafminer	28.0	1.8	3.5	0.5	0.1	0.7	13.0	0.3	1.0	15.0	1.2	3.0	43.0	2.0	2.9	23.0	1.2	3.1	20.4	14.5	1.1	0.8
Aphids ⁴	0.0	.	.	0.0	.	.	0.0	.	.	17.0	.	.	0.0	.	.	0.0	.	.	2.8	6.9	.	.
Flea beetle	5.0	0.4	1.9	3.5	0.2	1.3	96.0	9.2	6.1	1.5	0.1	0.6	30.0	1.7	3.9	99.0	22.6	16.8	39.2	46.4	5.7	9.0
Thrips	87.0	13.5	13.6	22.0	1.6	3.3	0.0	.	.	86.0	16.8	13.6	32.5	1.4	2.4	0.0	.	.	37.9	39.7	8.3	8.0

¹Severity was not estimated because plants were killed by the pest. ²Percentage of plants where insects were present, symptoms not registered.

Table 3. Incidence and severity of seed borne diseases, insect pests, and physical and physiological blemishes in six potato varieties in Ecuador (for the number of observations see *Materials and Methods*).

	Dolores			Chaucha Roja			INIAP-Yana Shungo			INIAP-Fripapa			INIAP-Gabriela			Única			Average			
	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	Incidence		Severity	
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	
	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	\bar{X}	\bar{X}	s	
Diseases																						
Cracking	14.5	0.3	1.0	1.5	0.0	0.4	8.0	0.1	0.3	33.3	1.1	3.6	37.3	1.6	5.0	15.5	0.6	3.7	18.3	14.1	0.6	0.6
Fusarium dry rot	3.0	0.5	5.7	35.8	3.0	7.3	3.0	0.2	1.4	6.8	0.3	1.8	0.3	0.0	0.3	2.8	0.6	6.6	8.6	13.5	0.8	1.1
Silver scurf	0.0	0.0	.	0.0	0.0	.	0.0	0.0	.	4.8	0.3	1.6	0.0	0.0	.	39.5	5.3	12.6	7.4	15.9	0.9	2.1
Black leg	0.0	0.0	.	1.0	0.8	8.0	2.0	0.5	4.1	0.0	0.0	.	0.0	0.0	.	0.3	0.1	1.3	0.5	0.8	0.2	0.3
Black scurf	88.5	5.1	6.2	83.3	2.6	3.3	42.0	0.4	0.6	85.0	2.4	6.8	88.3	3.8	7.4	95.8	4.6	6.5	80.5	19.3	3.2	1.7
Powdery scab	0.0	0.0	.	0.0	0.0	.	0.0	0.0	.	0.3	0.0	0.5	0.5	0.0	0.1	0.0	0.0	.	0.1	0.2	0.0	0.0
Virus																						
APLV	0.0	.	.	0.0	.	.	19.5	.	.	0.0	.	.	9.0	.	.	3.4	.	.	5.3	7.8	.	.
APMoV	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	6.0	.	.	0.0	.	.	1.0	2.4	.	.
PLRV	0.0	.	.	0.0	.	.	2.4	.	.	1.0	.	.	1.0	.	.	5.6	.	.	1.7	2.1	.	.
PVA	0.0	.	.	0.0	.	.	0.0	.	.	0.0	.	.	5.0	.	.	0.0	.	.	0.8	2.0	.	.
PVS	100.0	.	.	18.0	.	.	85.4	.	.	0.0	.	.	4.0	.	.	69.7	.	.	46.2	44.0	.	.
PVX	88.0	.	.	100.0	.	.	0.0	.	.	2.0	.	.	30.0	.	.	42.7	.	.	43.8	42.4	.	.
PVY	2.0	.	.	0.0	.	.	2.4	.	.	2.0	.	.	9.0	.	.	1.1	.	.	2.8	3.2	.	.
PYVV	0.0	.	.	0.0	.	.	2.4	.	.	2.0	.	.	11.0	.	.	1.1	.	.	2.8	4.2	.	.
Insects damages																						
White grub	10.5	0.4	1.8	5.0	0.2	1.7	16.5	1.8	7.4	1.0	0.0	0.6	6.8	0.3	1.5	10.0	0.9	4.2	8.3	5.3	0.6	0.7
Wireworm	11.5	0.2	0.7	1.3	0.0	0.3	0.0	0.0	.	8.5	0.1	0.7	15.8	0.3	1.0	0.0	0.0	0.0	6.2	6.7	0.1	0.1
Andean weevil	82.5	14.4	18.8	61.8	4.2	9.1	33.5	1.7	4.5	45.3	3.4	7.8	53.8	4.2	7.8	1.5	0.1	0.4	46.4	27.5	4.7	5.0
Tuber moth complex	0.0	0.0	.	2.8	0.1	0.5	0.0	0.0	.	0.0	0.0	0.0	0.0	0.0	.	25.3	1.0	3.8	4.7	10.1	0.2	0.4
Flea beetle	0.0	0.0	.	0.0	0.0	.	0.0	0.0	.	0.0	0.0	.	1.0	0.2	2.6	8.3	0.2	1.0	1.5	3.3	0.1	0.1
Physical and physiological issues																						
Mechanical damage	2.5	.	.	10.0	.	.	10.5	.	.	14.5	.	.	13.5	.	.	20.8	.	.	12.0	6.0	.	.
Misshappen tubers	0.5	.	.	1.5	.	.	12.5	.	.	2.3	.	.	0.0	.	.	1.5	.	.	3.0	4.7	.	.
Inmature tubers	35.0	.	.	51.5	.	.	99.5	.	.	0.8	.	.	63.0	.	.	33.3	.	.	47.2	33.2	.	.

Table 4. Main seed borne pests affecting yield variation. Quito, Pichincha.2012

Parameter ^{1,2}	Observations	Coefficient (g plant ⁻¹)	Partial R-squared (%)
Models per seed source			
Self-provided	539		
Intercept		1739.2	
PVS		-1180.0	38
PYVV		815.2	2
Total R-squared			40
Market	267		
Intercept		375.3	
Black scurf		24.0	7
Total R-squared			7
Formal system	297		
Intercept		1181.6	
PVS		-280.7	5
Mechanical damage		-184.4	2
Total R-squared			7
Models per variety			
Chaucha Roja	292		
Intercept		388.6	
PVS		-111.5	1
Black scurf		23.8	7
Total R-squared			8
INIAP-Fripapa	221		
Intercept		1220.6	
Mechanical damage		-299.6	9
Total R-squared			9
INIAP-Gabriela	197		
Intercept		2178.9	
PVS		-944.1	3
Black scurf		18.8	2
PYVV		526.1	4
Total R-squared			9
INIAP- Yana Shungo	76		
Intercept		835.8	
Mechanical damage		730.0	11
Total R-squared			11
Única	223		
Intercept		925.8	
PVS		-251.4	8
Black scurf		7.2	3
Total R-squared			11

¹ Parameters for multiple linear regressions were selected when *p-value* was lower 0.05. *P- values* ranged from < 0.001 to 0.03.

² PVS, PYVV, and mechanical damage were assessed based on their presence and absence; while black scurf was based on the percentage of severity on the seed tuber.

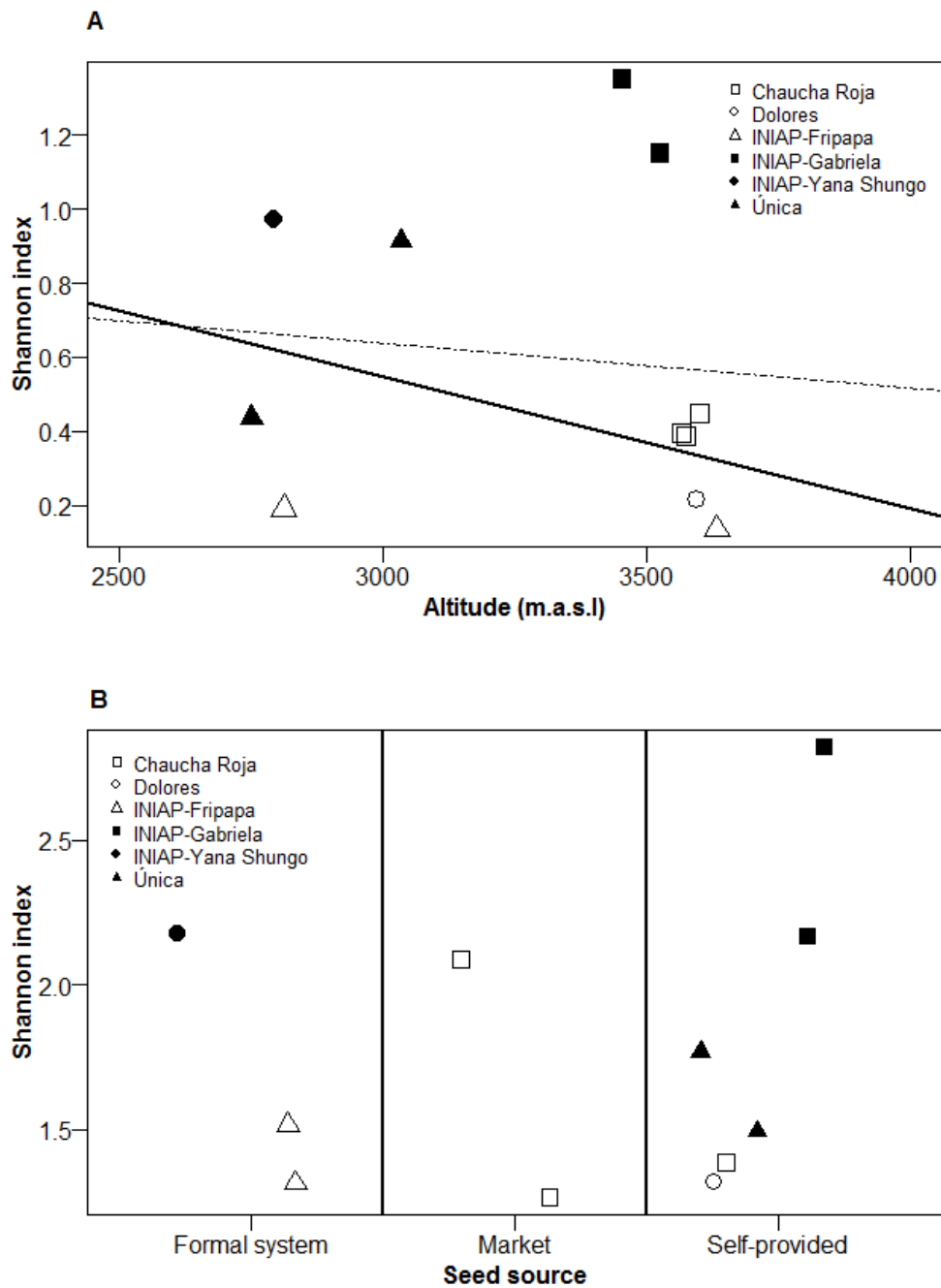


Figure 1. Seed borne pest diversity on seed tubers surveyed in three provinces in Ecuador. A. Effect of the altitude on virus diversity: dashed line represents a model including all varieties ($R^2 = 6\%$), and full line a model excluding INIAP-Gabriela ($R^2 = 22\%$). B. Pest diversity on tubers according to the three seed sources.

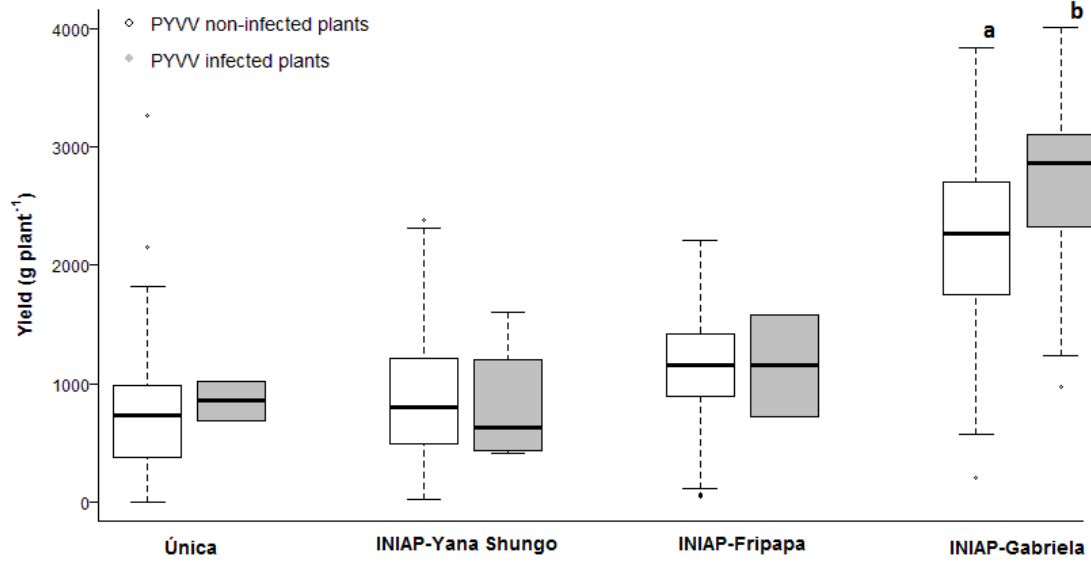


Figure 2. Effect of the presence of PYVV on yield in 4 potato varieties. Yield difference in the variety INIAP-Gabriela was analysed by a t-test. Different letters indicate significant differences according to the t-test (p -value < 0.01). The incidence of PYVV in each variety is in Table 3.