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1 **Title:** Disentangling yield level and yield stability when comparing multifaceted agricultural
2 production systems

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6 **Keywords**

7 Organic farming, agriculture models, intensification, Taylor's Power Law

8 **Abstract**

9 CONTEXT

10 Which type of agricultural production systems promotes the most stable yield is a matter of
11 debate, especially when comparing conventional and organic agriculture. Whether statistical or
12 agroecological, a relationship often exists between the level and stability of agricultural
13 production. In comparative studies of agricultural system yields, Taylor's Power Law often
14 applies (i.e., empirical law between mean and variance). Once this law tested, the issue is to
15 identify the proportion of stability that is determined by the agriculture type tested rather than by
16 the production level.

17 OBJECTIVE

18 In this short communication, we seek to disentangle biophysical and statistical effects related to
19 the comparison of yield stability along intensification gradients of agriculture.

20 METHODS

21 We carried out a short literature review and established a theoretical analysis.

22 RESULTS AND CONCLUSIONS

23 Tradeoffs between yield level and stability can be explained by analyzing potential effects of
24 limiting factors at different levels of fertilization and irrigation. However, the level of
25 intensification of cropping practices is not the only factor to consider; it is also necessary to
26 consider the pedoclimatic conditions, economic context, and biological regulations. In the short
27 and medium terms, the appropriateness of the production situation (i.e. the combination of

28 crops, management, soil and climate) and resource availability and dynamics is also crucial to
29 account for when designing resilient agricultural systems. In the long term, natural capital must
30 be conserved to ensure the level and stability of agricultural production.

31 SIGNIFICANCE

32 We highlight that identifying how production situations influence yield level and stability requires
33 detailed multiscale and multifactor approaches.

34

35

37 To control factors that limit or decrease crop yields, modern agriculture is based on
38 intensive use of industrial inputs such as fertilizers, irrigation, mechanical tillage and pesticides
39 (Duru et al., 2015). By reducing the yield gap in some regions of the world (Van Ittersum et al.,
40 2013), this intensification of agricultural systems freed them from several biophysical constraints
41 in agroecosystems but harmed the environment (Emmerson et al., 2016; Therond et al., 2017).
42 For example, irrigation decreases hydric deficit in the soil and thus increases yields (Zaveri and
43 Lobell, 2019), but the subsequent depletion of water resources can cause substantial local-to-
44 regional water scarcity (Rad et al., 2020). In addition, yields stagnation in some regions for
45 several years (Brisson et al., 2010) raises doubts about the ability of technological and genetical
46 progress to ensure food security for the world's growing population (Godfray et al., 2010),
47 especially under climate change and resource scarcity (Lobell and Tebaldi, 2014).

48 The stability of production, whether spatial or temporal, is an important criterion for
49 meeting the increasing global demand for food production (Schrama et al., 2018). The
50 increasingly frequent biophysical and socio-economic hazards challenge production stability
51 (Reidsma et al., 2010). After decades of examining effects of agricultural practices on crop yield
52 levels, yield stability has become a key area of study (Knapp and van der Heijden, 2018).
53 Several studies have investigated yield stability of different types of agricultural system,
54 hereafter agriculture model according to Therond et al. (2017), such as organic vs. conventional
55 farming (Knapp and van der Heijden, 2018). Other studies compare different management
56 practices such as low-input (Smith et al., 2007), no-till (Cociu and Cizma, 2015; Smith et al.,
57 2007), reduced tillage (Gaudin et al., 2015), or different types of fertilization (Berzsenyi et al.,
58 2000). Some studies also focus on the effects of crop rotation (Nielsen and Vigil, 2018), crop-
59 variety mixtures (Creissen et al., 2016), perennial vs. annual crops (Vico and Brunsell, 2018)
60 and the introduction of grain legumes (Reckling et al., 2018). Reidsma and Ewert (2008) show
61 that farm economic size has a positive effect on the stability in yield at the regional level. In their
62 review of effects of diversification and intensification on the resilience of agriculture systems,
63 Dardonville et al. (2020) find that input intensification did not always mitigate negative effects of
64 climate change on the dynamics of crop yield at field or farm levels. Of 145 comparisons, 67%
65 of intensification effects on resilience are negative or neutral, suggesting that intensification is

66 less often a relevant strategy to stabilize yield, increase the yield over years or have a high
67 probability of a high yield.

68 Another well-known example is the comparison between organic agriculture and
69 conventional (also called “industrial” or “intensive”) agriculture : the former, most often, has
70 lower yields (Ponisio et al., 2015; Seufert et al., 2012) but has more environmental benefits than
71 the later (Smith et al., 2019; Tuomisto et al., 2012). However, results of studies of the relative
72 stability of organic vs. conventional yields vary greatly. The thorough meta-analysis of Knapp
73 and van der Heijden (2018) confirms that organic systems have lower yield levels (-16% than
74 conventional systems) and suggests, like Smith et al. (2019), that they also have lower yield
75 stability when considering coefficients of variation. They suggest that organic fertilization is
76 more difficult to manage than mineral fertilization, which can cause the fertilization effect to vary
77 (depending on mineralization dynamics). Since the standard deviation of yields does not differ
78 significantly, they conclude, however, that the difference in yield levels between the two
79 agricultural models mainly explains why organic systems have lower yield stability. Other
80 studies shown the opposite trend (Schrama et al., 2018; Smolik et al., 1995) or no differences
81 (Lesur-Dumoulin et al., 2017; Stanhill, 1990), especially when individual crops are analyzed. For
82 example, Smith and Gross (2006) observe that maize yield is more stable (coefficient of
83 variation) in organic systems than in conventional least-diverse systems. Li et al. (2019)
84 observe that organic management of tomato increases yield stability (coefficient of variation).

85 The same difficulty is observed when comparing conservation agriculture and
86 conventional agriculture. Knapp and van der Heijden (2018) observe no significant differences
87 in yield stability regardless of how stability is measured. Rusinamhodzi et al. (2011) draw the
88 same conclusions for maize, but conversely Williams et al. (2018) observe that soybean yield is
89 more stable in conservation agriculture thanks to cover cropping than in conventional
90 agriculture.

91 As Therond et al. (2017) highlight, these results may diverge because categorizing
92 systems into broad categories such as conventional agriculture, organic or conservation
93 agriculture, hide a wide intrinsic variety of cropping systems and management practices with
94 different environmental and socio-economic performances, mean levels and dynamics.
95 Kirchmann et al. (2016) mention many pitfalls of comparing cropping systems categorized into

96 different agriculture models: comparisons require sound “conditions for equitable
97 evaluations...to avoid biased design, inappropriate interpretations and flawed conclusions” (see
98 also Gattinger et al. 2012). For example, conservation agriculture is often considered without
99 necessarily applying its three principles (soil coverage, low-tillage and crop diversity) at the
100 same time, which induces even more variability in the results observed (Pittelkow et al., 2015a;
101 Williams et al., 2018). Gaudin et al. (2015) explain that the effect of crop diversification or tillage
102 management on yield stability may be related to climate conditions: reducing tillage decreases
103 yield variability at the field level in favorable years but not in abnormal years (i.e. heat, dry, cold
104 or wet stress). In meta-analyses, even if individual experiments can control that compared
105 agriculture models have the same conditions (e.g. soil, climate, irrigation), the different
106 investigated experiments were conducted in different biophysical conditions (i.e. landscape
107 complexity) and agricultural practices (e.g. rotation complexity). These differences can lead to
108 contrasting results (Lori et al., 2017; Pittelkow et al., 2015b).

109 Nowadays, crop yield stability was measured using a wide range of indicators
110 corresponding to various concepts of stability (Reckling et al., 2021) such as the standard
111 deviation, coefficient of variation and slope of the Finlay-Wilkinson regression (e.g. in Knapp
112 and van der Heijden (2018); Li et al. (2019) and Macholdt et al., (2020). They can provide
113 different results depending on whether they assess absolute (e.g. standard deviation) or relative
114 variability (e.g. coefficient of variation) in the production level (Yongfan Wang et al., 2019).
115 Döring et al. (2015) highlight that Taylor's Power Law (TPL) indicates a potential relationship
116 between the logarithm of the variance and the logarithm of the mean of crop production. They
117 show that TPL holds true in many ecological studies and is applicable to many agricultural
118 systems at various scales (across environments, at global scale). When TPL applies, the
119 variance depends on the yield level, and differences in yield between agriculture models (e.g.
120 organic vs. conventional) bias the analysis of variance (Döring and Reckling, 2018). Dehghani
121 et al. (2008) analyze a few stability metrics using principal component analysis and show that
122 the coefficient of variation of yield is half-way correlated with yield level in comparison with other
123 stability metrics. Because of TPL, the coefficient of variation is biased, and thus using it to
124 estimate differences in stability is incorrect (Döring et al., 2015; Döring and Reckling, 2018). For
125 most of the agricultural datasets that Döring et al. (2015) test, TPL applies and the variance in

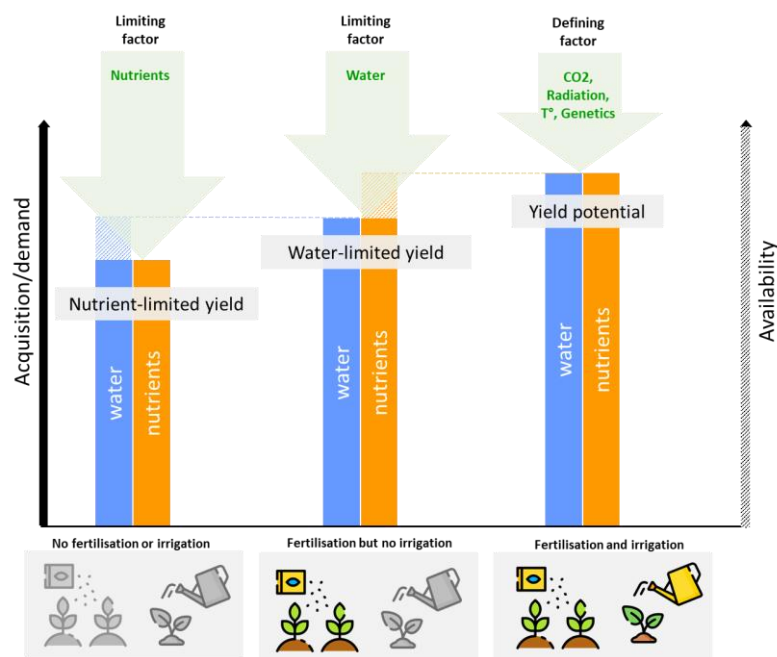
126 yield is positively correlated with the yield level. Conversely, in their meta-analysis of organic vs.
127 conventional systems Knapp and van der Heijden (2018) observe that (i) TPL does not apply to
128 size effects but does apply to observations, (ii) the standard deviation of yield is constant
129 regardless of the yield level, (iii) organic systems have lower yields than conventional systems
130 and (iv) relative stability (coefficient of variation) in yield differs between agriculture models due
131 to differences in yield levels. The challenge that emerges is thus to identify the part of the
132 variability that is due to the systems/models compared and not to the difference in yield level.
133 Unfortunately, studies that focus on yield stability rarely verify whether TPL applies (Döring et
134 al., 2015). To address this problem, several authors have developed methods to resolve
135 analytical bias when TPL applies by using the residuals of the TPL regression (Döring et al.,
136 2015) to correct the coefficient of variation (Döring and Reckling, 2018) or to consider the
137 coefficient of the fixed effect of the agriculture model in a linear regression that includes a mean
138 (Eq. 18 in Nakagawa et al., 2015). When TPL is observed, it is not yet known whether it is due
139 to purely stochastic or behavioral aspects (Arruda-Neto et al., 2012; Kendal and Jørgensen,
140 2011).

141 In the research field of comparing performances of agriculture models, there is still a
142 research gap regarding the factors that affect and explain yield stability (Döring et al., 2015).
143 The example of the numerous comparisons between conventional vs. organic systems shows
144 the necessity of a sound assessment of the effect of the agriculture model on the yield stability.
145 In this short communication, we use the theory of limiting factors of agricultural production, to
146 explain agronomical processes underpinning relations between yield level and stability. We
147 highlight the importance of considering short-, medium- and long-term dynamics and
148 characteristics of the production situations to analyze yield stability. To conclude, we propose
149 an agronomic research agenda for crop yield stability analysis.

150 **2. Agronomic principles of yield level and stability**

151 From one side, according to the Liebig's law, the most limiting production factor
152 constraints the production level (de Wit, 1992, Figure 1). The different production factors are
153 related to climate (CO₂ concentration, radiation, temperature, precipitations), genetics, water,
154 nutrients, and biotic pressures (Van Ittersum et al., 2013). On the other side, once established,
155 biomass quantity determines the plant's water and nutrient demands: the more biomass, the

156 more water and nutrients it demands. The availability of soil water and nutrients determines
 157 whether these demands are met or not (de Wit, 1992). In agricultural systems, the influence of
 158 fertilization and irrigation are related: increasing one increases crop demand for the other
 159 (Chukalla et al., 2020). Consequently, the demand for and availability of water and nutrients
 160 influence each other. Finally, biotic pressures, also called regulation factors (Ittersum and
 161 Rabbinge, 1997), can reduce the yield determined by the water and nutrient availability and so
 162 stresses. We focus in this section on biophysical factors (water, nitrogen), which determine the
 163 majority of crop production (Beza et al., 2017).

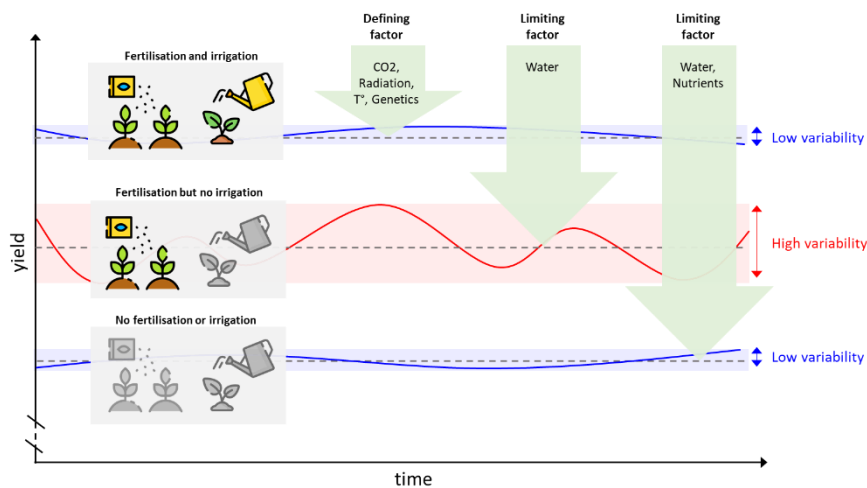


164

165 Figure 1. Defining and limiting factors according to intensification levels (fertilization and
 166 irrigation) of crop/grassland production. (*Hypothetical data*)

167 Regarding yield stability, in most of the datasets that Döring et al. (2015) test, the
 168 relationship between the logarithm of the standard deviation of yield and the logarithm of mean
 169 yield is positive and linear, which indicates that yield variability increases with yield level. When
 170 analyzing biophysical processes that underlie this relationship, we assume that variability in
 171 yield due to climate variability (e.g. drought, heat) is intrinsically related to the yield (biomass)
 172 level (Figure 2). This might be explained by the influence of biomass quantity on the demand for
 173 resources required for growth. By reasoning at the level of fertilization and irrigation we can
 174 attempt to explain the relationships between the level of yield and its variability (Figure 2).

175 First, without fertilization or irrigation, the nutrient-limited yield (low biomass) results in
 176 low plant water demand, which can be met more easily by the soil water available, and thus
 177 climate variability may have little influence on yield. In other words, yields limited by nutrients
 178 are less affected by climatic conditions, as these are not the limiting factors of production (Van
 179 Ittersum et al., 2013). When applying fertilization, the higher yield and biomass increase plant
 180 water demand, which makes yield more sensitive to water availability. In other words, yields
 181 limited by water may fluctuate more because of fluctuations in climate (Van Ittersum et al.,
 182 2013). Applying fertilization and irrigation, allows to meet higher nutrient and water demands
 183 and makes yield nearly insensitive to climate variability (when irrigation water is not limited).
 184 Consequently, rainfed systems with high production due to high fertilization, and thus high water
 185 demand, are expected to be more sensitive to climate variability than those with lower
 186 production or those that are irrigated. When intensification and production level are not
 187 considered, the yields of non-intensive situations and the most intensive situations may present
 188 similar standard deviation (i.e. low sensitivity to climate variability), different coefficients of
 189 variation and different explanatory factors. To resume, the limiting factor may be nutrients in the
 190 non-intensive system (lowest yield), water in the fertilized system (medium yield) due to heat
 191 and drought, and genetics in the fertilized and irrigated system (highest yield).



192

193 **Figure 2. Effects of production level and input intensification on production variability in**
 194 **a crop/grassland system at the field level due to resource availability (water, nutrients)**
 195 **for a given climate and soil. (Hypothetical data)**

196 Supporting this conceptualization, Reidsma et al. (2008b) show that farms with lower
197 yields (and less intensification) are less sensitive to climate disturbance in regions that have
198 already adapted to recurring drought and increasing temperatures (e.g. Mediterranean regions).
199 Berzsenyi et al. (2000) show that wheat and maize yield stabilizes when the crops are not
200 fertilized. Smith et al. (2007) draw the same conclusion for low-input systems. For grasslands,
201 Wang et al. (2019) show that variability in production increases significantly as production
202 increases. Consequently, we assume that the varying outcomes of studies comparing
203 conventional to organic or conservation agriculture stem from differences in the levels of
204 intensification involved and thus, the limiting factor of the yield.

205 **3. Short and long-term effects**

206 While some agricultural practices can provide desired yield dynamics in the short
207 term, they can fail to do so in the medium or long terms (Coomes et al., 2019). Consequently,
208 short-term studies may not be able to identify or highlight middle- or long-term effects (Müller et
209 al., 2016). From a middle-term perspective, the dynamics of soil natural capital (e.g. soil organic
210 matter) and local/regional resources (e.g. water) can influence dynamics strongly, especially
211 those of the level and stability of agricultural production (Dardonville et al., 2021; Weyers and
212 Gramig, 2017). Agricultural systems can exhibit dynamics in the short term (e.g. season, year or
213 few years) while experiencing degradation in soil natural capital and local resources due to
214 intensive management and a high production level (Dardonville et al., 2021). For example,
215 intensive use of groundwater for irrigation can result in a water shortage making irrigation more
216 difficult (costlier), limiting its application or rendering it impossible (de Graaf et al., 2019). This
217 problem also occurs in agricultural systems that use soil natural capital without recycling it, such
218 as those that deplete soil organic matter (Drinkwater and Snapp, 2007) or organic systems that
219 use soil phosphorus reserves without supplying organic matter to replace the phosphorus
220 exported (Kirchmann et al., 2009; Oelofse et al., 2010). Hence, Williams et al. (2018) show that
221 improving soil properties, especially soil organic matter content, increases yield stability.

222 Although less intuitive, the dynamics of soil resource use can influence yield dynamics
223 in the short term. Plant efficient resource acquisition during a given period (e.g. by exploring soil
224 horizons (Barkaoui et al., 2016; Vico and Brunsell, 2018)) can initially result in higher biomass
225 production or stability (e.g. at the beginning of a season) but also greater depletion of soil

226 resources. If a disturbance (e.g. drought) lasts or repeats, depleted resources (e.g. soil water,
227 nutrients) and the large amount of biomass with high water and nutrient demands will influence
228 biomass variability at the end of a season (Zavalloni et al., 2008).

229 **4. Effect of crop diversification and adequation to the production situations**

230 Renard and Tilman (2019) reveal that yield stability increases with irrigation, but more
231 so due to species diversity and even more so due to diversity in crop functional groups (e.g.
232 legumes, cereals). They claim that diversification could be a better strategy for adapting to
233 climate change than irrigation in countries where water is unaffordable or insufficient, as is the
234 case for 30-47% of rainfed wheat and maize croplands in the world (Wang et al., 2021).

235 At the global scale, Ben-Ari and Makowski (2014) identify regions that drive worldwide
236 stability in maize and rice yields and suggest that developing croplands in some regions could
237 increase or decrease this stability in global production. Ben-Ari and Makowski (2016) identify a
238 relatively constant tradeoff over time between yield level and stability for maize and for all crops
239 aggregated (maize, rice, soybean, and wheat). They identify regions in which to develop crops
240 to achieve an optimal relationship between yield level and stability and mention that “expected
241 yield differences can be explained by contrasts in production systems and intensification levels”
242 and by climates. This indicates that the type and management of crops must be adapted to the
243 local soil, climate and (water) resources, i.e. to the pedo-climatic conditions of the production
244 (Aubertot and Robin, 2013).

245 Although it is not the focus of this article, a broad field of literature makes assumptions
246 about the influence of genetics and biotic factors on the yield stability. For example, Kahiluoto et
247 al. (2019) and Snowdon et al. (2019) discuss the European wheat response diversity reduction
248 since the beginning of the 21st century and the role of genetic selection. Murphy et al. (2007)
249 highlight that wheat varieties are particularly suited to provide high and stable yields, but only
250 with intensive inputs. Regarding biotic factors, Knapp and van der Heijden (2018) suggest that
251 natural pest control, encouraged in organic farming systems, follows predator-prey dynamics
252 that are subject to lag times and variability. In the UK, Redhead et al. (2020) found that more
253 stable yields were observed in landscapes with both a high coverage of arable land and semi-

254 natural habitats evenly distributed throughout the landscape, favoring natural biological
255 regulations (pollination and biological control).

256 **5. Research Agenda and conclusion**

257 We show that there is an important variability in conclusions of studies analyzing yield
258 stability of different agricultural systems. Many of these studies do not consider TPL or key
259 differences between production situations that determine yield level and stability: crop
260 management as irrigation and fertilization, diversification... Given these limits, we propose
261 several research paths to increase the quality of studies and capitalization of results and
262 conclusions.

263 We emphasize the importance of considering the production level when comparing
264 systems and its statistical and agroecological relationships with its dynamics. TPL should
265 always be tested and its bias excluded as proposed by Reckling et al. (2021). As statistical
266 procedure for testing TPL, Taylor et al. (1988) recommend at least 15 measurements of yield
267 per pair of the logarithm of the variance and the logarithm of the mean of crop production and at
268 least 5 pairs, which is rarely observed in the studies reviewed by Döring et al. (2015).

269 Thus, we strongly recommend considering and describing in detail the cropping
270 practices (e.g. irrigation vs. rainfed systems, level of irrigation and fertilization in regards of crop
271 demands) and soil and climate conditions. At a minimum, we consider it necessary to describe
272 (i) nitrogen (mineral and total) and irrigation water input levels in order to incorporate input level
273 classes into the statistical analysis (e.g. Yingcheng Wang et al. (2019)), (ii) the soil, using a soil
274 depth indicator to determine the available water capacity potential and the organic matter
275 content in the top 30 cm of soil (e.g. Gross and Glaser (2021)), and (iii) the climate, using
276 Köppen–Geiger climate classification (e.g. de la Cruz et al. (2023)). These factors determine the
277 dynamics of crop-soil-climate interactions and thus yield dynamics. Relationships between the
278 yield level and dynamics of limiting and reducing factors should be analyzed or at least
279 discussed.

280 Finally, even for a short-term study, we recommend investigating and, if possible,
281 evaluating middle- or long-term effects of intensification on endogenous (e.g. natural capital) or
282 exogenous (e.g. local) resources and, in turn, on the stability of agricultural production. We

283 emphasize the importance of considering both short- and long-term issues to highlight that
284 degrading natural capital in the present will create negative feedback loops in the future. This is
285 especially important because promising agriculture models are based on ecosystem services
286 (such as erosion control, soil maintenance and water, nutrient and carbon cycling) and depend
287 on the quality of natural capital (Dardonville et al., 2022; Smith et al., 2020).

288 More than ever, the intensification level and the associated stability level of production
289 need to be reintegrated into the design and the multicriteria evaluation of agricultural systems.
290 We hope that this review contributes to the debate on the strengths and weaknesses of
291 intensification and how to meet local-to-global objectives for agricultural system production and
292 associated food security. Agricultural stakeholders and society must take a stance on the
293 compromise between short- and long-term objectives for production. In the quest for agricultural
294 sustainability, in the context of climate change and associated increasingly extreme climatic
295 events, it may be necessary to redefine objectives: less focus on the production level and more
296 focus on desired dynamics, such as conservation or development of natural capital and
297 associated ecosystem services (Tittonell et al., 2016).

298 **CRedit authorship contribution statement**

299 Manon Dardonville: Conceptualization, Writing – original draft, Visualization, Investigation. Jean
300 Villerd: Investigation. Olivier Therond: Conceptualization, Writing – review and editing,
301 Supervision.

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