El Niño-Southern Oscillation impacts on grape yields in Santana do Livramento, Brazil: understanding and early warning of crop failure conditions[1]

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ABSTRACT

El Niño-Southern Oscillation (ENSO) is an important source of year–to–year fluctuations in the whole global climate system and in the southern Brazilian climate. El Niño events affect this region, imposing unfavorable weather conditions (rainy/humid/overcast) during critical grapevine phenological stages, compromising yields in the current and following crop seasons. The analysis of 29 crop cycles revealed patterns about grape yield oscillations in Santana do Livramento, Campanha Gaúcha, RS, Brazil. Yield deviations showed correlations with the Oceanic Niño Index (ONI) 3 months running means centered in November. La Niña events correlate with yield oscillations close to or above the tendency line. El Niño events are linked to various results, including the lowest and the highest yields. The four largest crop failures happened in El Niño events, while the three most severe of them happened in cases of early El Niño consolidation. The seven lowest yields were linked to El Niño, or low or descending yields in the previous year (s), or all these factors combined. Simple criteria allowing early warning of crop failure conditions were defined: ONI (or the monthly Niño - 3.4 Index) ≥ +0.5 °C in July (or earlier); and low or descending yields in the previous year (s).

Keywords: *Vitis vinifera*; wine; ENSO; oceanic niño index; campanha gaúcha.

INTRODUCTION

The phenomenon El Niño-Southern Oscillation (ENSO) and its warm (El Niño) and cold (La Niña) phases influence on extreme climate variability in several regions of the world. Among them, it is possible to highlight southeastern South America, comprising areas within Uruguay, Argentina, Paraguay and southern Brazil (Cunha *et al.*, 2001). El Niño is characterized by warmer surface water temperatures in the Pacific Ocean and weakening of equatorial trade winds. La Niña presents the opposite characteristics. Neutral conditions are comprised between the minimum thresholds characterizing El Niño and La Niña (Timmermann *et al.*, 2018). Either the cold or the warm phase occur with irregular frequency and different levels of intensity (e.g. weak, moderate, or strong), and commonly persist for 12–18 months (Cunha, 2001).

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(NOAA) keeps records and defines ENSO events based on the Oceanic Niño Index (ONI) – 3 month running mean of anomalies (calculated based on Huang *et al.*, 2017) in the Niño 3.4 region (5°N–5°S, 120°–170°W). The events are defined as periods when the ONI thresholds of ± 0.5 °C are reached or exceeded and maintained for 5 or more consecutive months (NOAA, 2021). Early warning of ENSO occurrence is of paramount importance to at-risk societies and environments, once it imposes remarkable societal and ecological impacts (Glantz & Ramirez, 2020). ENSO also represents 'the single most prominent source of crop production variability in South and North America (Anderson *et al.*, 2017).

The climate of Santana do Livramento (in its region, Campanha Gaúcha, and in most southern Brazil) is classified as Cfa (temperate, without dry season, and with hot summer), following the classification system of Köppen–Geiger (Peel *et al.*, 2007). Campanha Gaúcha is currently the second biggest grape producing region in Brazil. It is responsible for suppling the grapes for producing 31% of the total volume of Brazilian wines elaborated with grapes from *Vitis vinifera* cultivars (Embrapa, 2020).

Rainfall is notably influenced by ENSO in the southern–most state of Brazil (Rio Grande do Sul, where Campanha Gaúcha is located). Generally, El Niño is correlated with higher rainfall and La Niña is correlated with lower rainfall in any season of the year (Matzenauer *et al.*, 2018). The spring becomes notably rainier during El Niño events (Matzenauer *et al.*, 2018; Nicknich *et al.*, 2005). In Rio Grande do Sul, relative humidity is increased by the occurrence of El Niño (Cunha, 2001). In Campanha Gaúcha, during El Niño, the probabilities of rainfall above the average are 55–65% higher in October and 75–85% in November, which presents a monthly rainfall anomaly between + 80 and + 100 mm (Marques *et al.*, 2003). Nearby Campanha Gaúcha (in Pelotas), during El Niño and La Niña events, rainfall is the climate variable showing the largest deviations. Anomalies occur mainly in the October-December quarter. In El Niño events, November is the month that is affected by the largest deviations from the historical means: higher rainfall; lower solar radiation; and lower evapotranspiration. In contrast, La Niña caused lower rainfall during October-January and higher solar radiation during October-December (Steinmetz *et al.*, 1999). In sum, in the region under study, El Niño is highly correlated with rainy, overcast (reduced solar radiation) and humid weather during spring.

In Santana do Livramento, the grapevines present the following general phonological patterns, which present some variability of days or weeks, depending mostly on cultivar and weather. Budbreak happens in September. Bloom happens during October-November. Fruit-set and initial berry development are conditioned to effective pollination during bloom and might continue during December (Costa, 2011).

Yield potential starts to be determined (at least) as early as during the spring of the previous crop cycle. Uncommitted primordia are formed from budbreak to bloom and can differentiate into either inflorescence, tendril or even shoot primordia. Inflorescence differentiation begins around bloom and may continue until the buds enter dormancy. Bud fruitfulness – the maximum number of inflorescences per latent bud – seems to be determined around 3 months after budbreak (Alleweldt & Ilter, 1969; Keller, 2020). Overcast conditions during bloom and fruitset generally affect fruitfulness negatively (Keller & Koblet, 1995; Keller, 2020). Other abiotic factors such as water and nitrogen levels also affect bud fertility (Guilpart *et al.*, 2014). Fruitfulness will exert effects on the yields of the following crop season, more than one year later.

Once fruitfulness has been stablished in the previous crop season, the following spring and its conditions for budbreak, shoot development, bloom, pollination and fruitset are the next determining factors for that crop season's yield (Keller, 2020). Rain before and during bloom can cause flowers to drop without opening. Rainfall is also linked to reduced pollen viability or germination rate, what can lead to excessive flower abscission and poor fruitset (Vasconcelos *et al.*, 2009). The fruitset is affected by virtually any factor reducing photosynthesis. Frequent rainfall is unfavorable for optimum photosynthesis (Garrido *et al.*, 2017; Vasconcelos *et al.*, 2009). In sum, 'ideal conditions during bloom, leading to maximum fruitset, are practically identical to those required for maximum inflorescence initiation' (Keller, 2020). In other words, the unfavorable conditions compromising the yield in a certain crop season are also compromising the yield potential for the following crop season.

This research focused on understanding the patterns of grape yield oscillations in Santana do Livramento and understanting the relationship between these oscillations and the occurrence of ENSO. It also aimed to stablish criteria for forecasting, warning of and mitigating crop failures.

MATERIAL AND METHODS

Data about grape yields in Santana do Livramento were obtained for the 29 crop seasons between 1993 and 2021. The dataset was recorded and maintained by the company 'Vinícola Almadén' as part of their internal control protocols, comprising all their own private vineyards (in an area surrounding 30°47'26"S, 55°22'29"W). The vineyards included 11 white grape cultivars and 18 red grape cultivars (all *Vitis vinifera*) growing on a total area ranging from 374 to 575 ha. These vineyards were mostly initiated in the 70ths; in the 80ths the total planted area was already larger than 400 ha. The need of replanting some areas has caused shifts in total planted and harvested area during the last 3 decades. Invariably, yields were consistently calculated in tons per hectare (total harvested grape weight divided by total harvested area).

Data about the temperature oscillations in the Niño 3.4 region was obtained from the National Oceanic and Atmospheric Administration, NOAA (NOAA, 2021). The latest Oceanic Niño Index (ONI) values collected were according to the Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5) (Huang *et al.*, 2017). Complete data regarding both ONI values and monthly Niño 3.4 Index values, fully available online (NOAA, 2021), were used as databases for analyses. An analysis of ONI values and ENSO occurrence (NOAA, 2021) was conducted in order to select the single most representative quarter (or as referred in this research, the month in the center of the quarter) to capture the maximum ONI oscillations within El Niño/La Niña events. In other words, the ONI monthly value that most frequently coincides with the most extreme ONI value in each ENSO event was defined. This ONI value was used to provide a comparable estimate for the intensity of El Niño or La Niña events.

November centered ONI values – or 'OND' ONI values, i.e. ONI values corresponding to the October-November-December quarter – were the most representative (Figure 1). Along the 29 crop seasons, there were 9 El Niño, 12 La Niña, and only 8 Neutral cases (Figure 1). In 13 out of 21 events (9 El Niño events plus 12 La Niña evets), the maximum ONI oscillation corresponds to the ONI value in November. The maximum ONI oscillation was reached in December or January in other 6 and 2 cases, respectively. Within these 8 cases, the oscillation beyond the ONI value observed in November was more often only 0.1 °C (in 5 events), 0.2 °C (in 3 events), and 0.3 °C (in 1 event). There are further reasons for considering November ONI values, as revised in the introduction: commonly, it is the month showing the most remarkable combination of all weather deviations caused by El Niño; and it is a critical month for fruitset and yield definition.

Dispersions and barplots were constructed with the variables under study (ONI values, years and all the yield related variables) in order to allow the visualization of data, tendencies and correlations between the variables. When applicable, tendency lines (using linear, exponential, and polynomial regression equations) were drawn, tested, and selected based on their coefficient of determination (R^2).

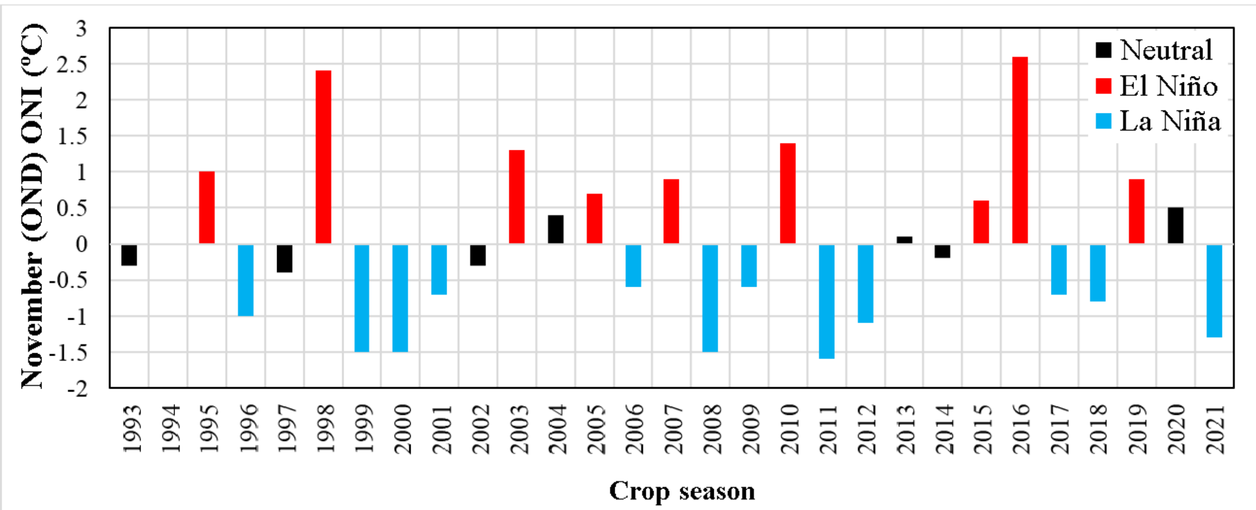

Figure 1: November (OND) ONI values (NOAA, 2021) in the crop seasons 1993-2021.

Along the 29 crop seasons, different crop management practices (mainly pruning techniques and fertilization regimes) were gradually introduced and implemented. Identifying the effects of these practices along the crop seasons and isolating them from the annual effects of climate variability was mandatory. Therefore, a tendency line was fitted on the dots in a plot of years *x* yields and some calculations were performed as described next.

Yield shifts (absolute and relative) were calculated (Equations 1 and 2) annually, in relation to each previous year's. Yield deviations (absolute and relative) were calculated (Equations 3 and 4) annually, in relation to the theoretical annual yield defined by the best fitting tendency line and its regression equation in a plot of years *x* yields. Absolute yield deviations were calculated following procedures already employed in previous research (Cunha *et al.*, 2001). Yield shifts and yield deviations were considered as better estimates than yields for expressing yield oscillations caused by climate variability.

[*Absolute yield shift*] = [*Yield*] – [*Previous year's yield*] (Equation 1)

[*Relative yield shift*] = [*Yield*] / [*Previous year's yield*] (Equation 2)

[*Absolute yield deviation*] = [*Theoretical yield*] – [*Yield*] (Equation 3)

[*Relative yield deviation*] = [*Absolute yield deviation*] / [*Theoretical yield*] (Equation 4)

RESULTS AND DISCUSSION

3.1 Yields, absolute yield deviations and relative yield deviations

Yields (Figure 2a) clearly showed a tendency along the period under study. A polynomial tendency line could be fitted with a coefficient of determination of 0.5. Yields in the 16–18 $t.ha^{-1}$ range in the first crop seasons decreased to around 8 $t.ha^{-1}$ in 2011 and showed a slight increase since 2017, reaching 11 $t.ha^{-1}$ in 2021. These tendencies are supposed to be unrelated to climate. They result from technological or crop management aspects. Along the 29 crop seasons the company had 3 different owners, with different objectives and policies. These largest yield differences (i.e. between 16–18 $t.ha^{-1}$ and 8 $t.ha^{-1}$) arise first of all from pruning techniques and secondly from fertilization regimes. Leaving less buds in winter pruning and/or reducing fertilization were the practices responsible for lowering yields.

Absolute yield deviations showed considerable variability (Figure 2b), ranging from +5.14 $t.ha^{-1}$ to -7.55 $t.ha^{-1}$. Accordingly, relative yield deviations (Figure 2c) – calculated relatively to the tendency line in Figure 2a – ranged from +56% to -75%. Considering relative yield deviations was particularly important in this study because it allowed to compensate the whole range of average yields described by the tendency line shown in Figure 2a (8–18 $t.ha^{-1}$, approximately) and make the yields of all the 29 crop seasons more directly comparable. Some logical patterns and correlations between November centered ONI values (Figure 1) and relative yield deviations (Figure 2c) can be pointed out in Figure 3.

Out of the 29 crop seasons, the three largest relative crop failures (negative relative yield deviations, between -49 and -75%) happened in El Niño events (Figure 2c). That is already a fact showing that ENSO does affect yields in the region under study. Another remarkable feature is that El Niño events are very scattered on Figure 3, what indicates that, under El Niño events, multiple scenarios might be expected. On the other hand, La Niña cases are even less scattered than Neutral cases, display mostly positive relative yield deviations and no large crop failures (the most negative relative yield deviation was -9.5%). Therefore, La Niña is the most positive condition for yields in this region, causing less unpredictability, high yields and no considerable crop failures.

Regarding predictability, even though these general negative and positive effects of respectively El Niño and La Niña on yields can be observed at a first glance, some additional patterns must be understood. Further observations on the ONI values, as well as the monthly Niño 3.4 Index values (NOAA, 2021), and yields (Figure 2a) allowed to reach new important insights discussed in the next subsections (3.2 and 3.3).

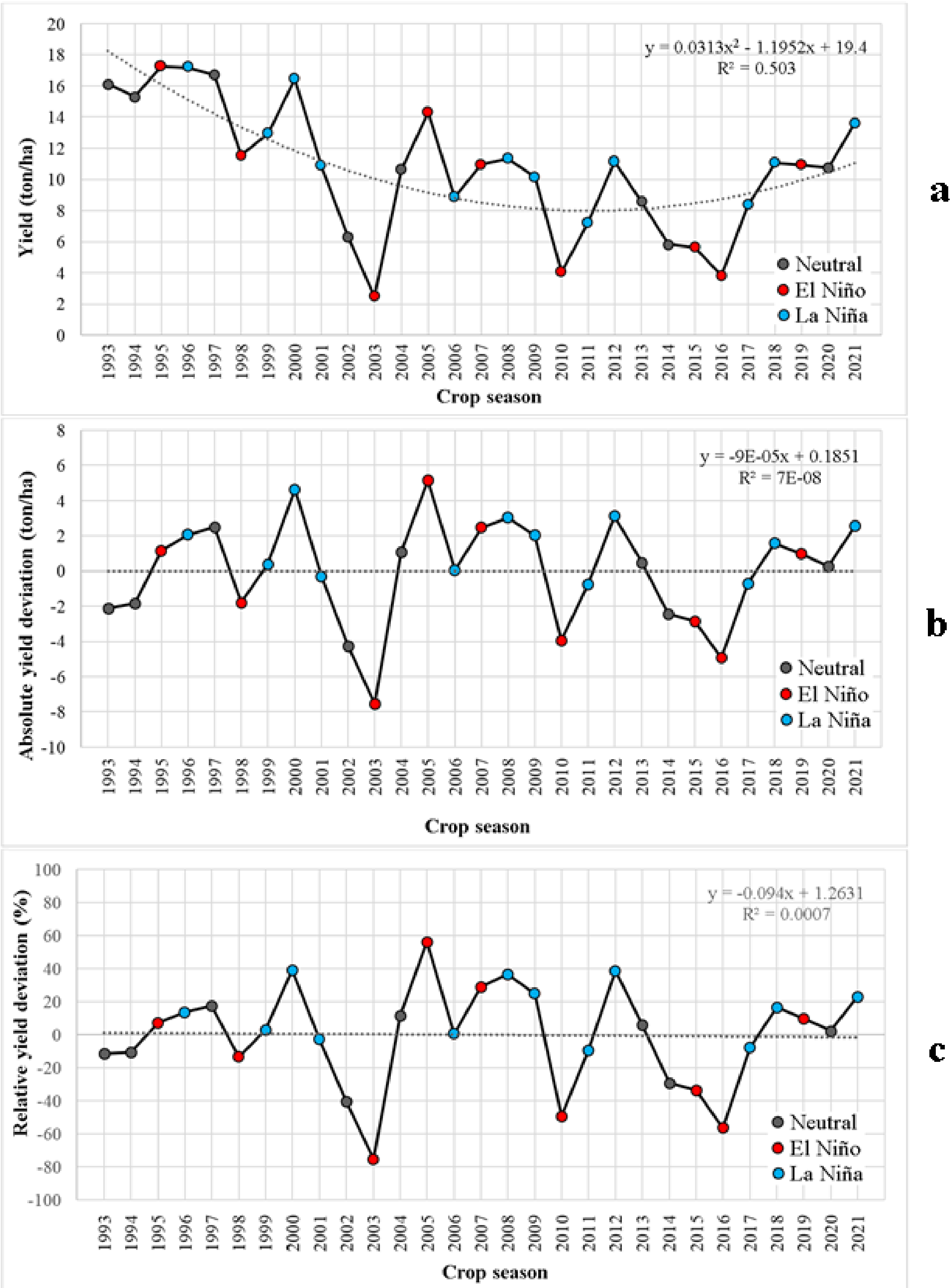

Figure 2: Yields (a), absolute yield deviations (b), and relative yield deviations (c) in the crop seasons 1993-2021.

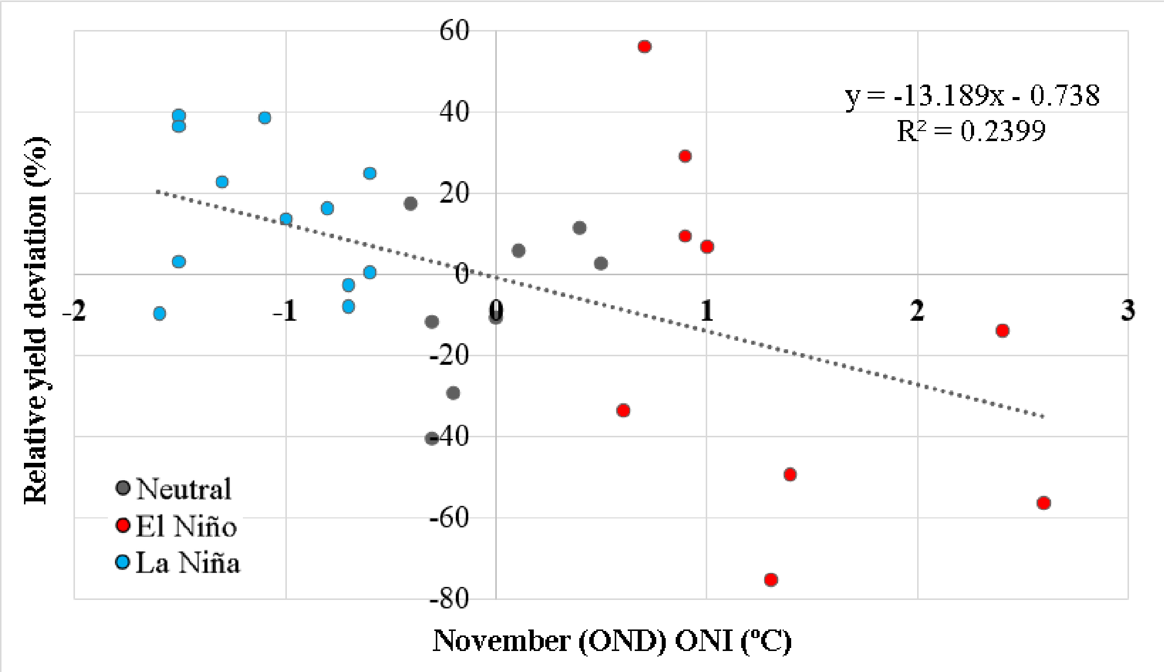

Figure 3: November ONI values (NOAA, 2021) *versus* relative yield deviations in the crop seasons 1993-2021.

3.2 Early El Niño consolidation versus late El Niño consolidation

The three largest relative crop failures (2003, 2010 and 2016) and the seventh largest relative crop failure (1998) (Figure 2b) were the four only cases – referred here as cases of 'early El Niño consolidation' – in which the November (OND) ONI reached or surpassed + 1.3 °C (Figure 3) – and the monthly Niño–3.4 index surpassed + 1.4 °C. These were also the only four events in which the ONI was ≥ + 1 °C already in October. The two largest crop failures also share the common feature of a very early El Niño consolidation, respectively for the 2003 and 2016 crops seasons: the + 0.7 °C ONI and the monthly Niño 3.4 Index thresholds were reached in June and April (this was actually a second consecutive El Niño event); the + 1 °C ONI and the monthly Niño 3.4 Index thresholds were reached in September and June; the fifth consecutive months displaying an ONI above + 0.5 °C were October and July. The only other similarly early El Niño consolidation happened in the 1998 crop season (it was actually earlier than in the case of the 2003 crop season) and is further discussed in the subsection 3.4 as a reasonable exception among these cases.

It is important to emphasize that not all the events commonly classified as El Niño impacted negatively on yields. El Niño events displaying November ONI values ≤ + 1 °C – referred here as cases of 'late El Niño consolidation' – presented positive relative yield deviations in four cases (1995, 2005, 2007 and 2019) out of five cases (the exception is 2015). It is also important to correlate the facts that these El Niño events of late consolidation and those of early consolidation were respectively events of weaker and stronger intensity (maximum positive ONI oscillation). Still, considering the scope of this research, understanding them as events of early or late consolidation is thus more appropriate for warning purposes.

In sum, two general El Niño patterns were observed, forming two groups of El Niño events (with their respective current crop season's typical yield response), either: early El Niño consolidation (and low yields); or late El Niño consolidation (and high yields). There was only one reasonable exception within each group: one, among the four cases of early El Niño consolidation (1998, with a reasonably high yield); and another, among the five cases of late El Niño consolidation (2015 with the fourth lowest yield and the fifth most negative relative yield deviation). Those exceptions led to other insights described in the next subsection (3.3).

3.3 High or ascending yields versus low or descending yields

By observing the progression of consecutive yields (Figure 2a) and the difference between each crop season and its preceding ones, other enlightening patterns can be pointed out. 2003 and 2016 (the two largest crop failures, which happened under the worse El Niño scenario, i.e. early El Niño consolidation) were also successors of crop seasons with already descending yields as well as yields below the tendency line. In contrast, before 1998 (which was also threatened by the worse scenario of very early El Niño consolidation but did not present a comparable severe crop failure), the three preceding crop seasons had yields above the tendency line and all the five preceding crops seasons were among the six largest yields in the whole time series of 29 crop seasons. The opposite complement to this logic pattern was 2015 (which is among the cases of late El Niño consolidation but with low yields), preceded by the fifth lowest yielding crop season in the whole time series (2014) and two crop seasons of already descending yields (2013 and 2014). In contrast, just four crop seasons later, in 2019, another case of late El Niño consolidation, yields above the tendency line were observed, in this case after two consecutive La Niña events and crop seasons of ascending yields. Further corroborating, among the neutral years, the two largest crop failures (2002 and 2014) also had their preceding years with descending yields (Figure 2a).

These facts suggest that not solely the early El Niño consolidation caused noticeable negative effects on yields. Yields tended to be lower if the yield (s) in the preceding year (s) were low and/or already descending. The six largest crop failures – comprising the two cases of the neutral years mentioned above – were all linked to descending yields in the previous year (s). It is already well understood in the literature, as reviewed in the introduction, that the optimum weather conditions for flowering and fruitset (influencing on current crop season's yields) are similar to those required for maximum inflorescence initiation (influencing on following crop season's yields). 'This is the likely reason to explain why years in which the shoots carry more clusters than usual often follow years with above–average fruit set' (Keller, 2020).

This hypothesis about the influence of previous year (s) conditions can be also suitable to (at least partially) explain the remarkable periods of descending yields (Figures 2–4): 2000–2003 e 2012–2016. Following the same logic – but in the opposite direction – years with normal or ascending yields should be favorable to the maintenance of satisfactory yields for the following year(s). With this concept in mind, it is possible to observe that there are, indeed, sequences of crop seasons with yields close to or above the tendency line (Figure 2a): 1993–1997; 1999–2001; 2004–2009; 2011–2013; and 2017–2021.

Another hypothesis that might be even more straightforward to provide further explanations for yield shift patterns is that the yield negative shifts are mostly gradual (Figure 2a). The two largest negative relative yield shifts (calculated with Equation 2) were -61 and -60%, respectively in 2003 and 2010 (cases of early El Niño consolidation, not surprisingly). Even though the relative shifts were almost identical, they corresponded to quite different yield shifts (calculated with Equation 1) of -3.8 and -6.1 ton/ha and resulted in yields of 2.5 and 4.1 ton/ha, respectively. The fourth largest negative yield shift was -5.2 ton/ha in 1998 (also in a case of early El Niño consolidation), close to the average between the just mentioned -3.8 and -6.1 ton/ha. However, in that crop season (1998) this similar yield shift of 5.2 ton/ha represented only -31% of relative yield shift (approximately the half of the just mentioned -61 and -60%) and still resulted in a yield of 11.55 ton/ha. From the perspective of a company which has to cover at least fixed costs, producing under the worse weather conditions either 2.5, 4.1 or 11.5 ton/ha are three very different scenarios. Therefore, it becomes clear that paying attention to and investing efforts and resources on preventing descending yields is strategic to mitigate upcoming crop failures.

3.4 Predicting and warning of crop failures

Considering all the information discussed so far, it is possible to stablish that the severity of crop failures were the highest when the following was observed: early El Niño consolidation; and/or low and/or descending yields in the previous year(s).

In all the three cases with earliest El Niño consolidation (1998, 2003, and 2016 crop seasons) when the ONI (and the monthly Niño–3.4 Index) threshold of + 0.7 °C were reached or surpassed in June (or as early as April or May), lower yields than in their 5 immediate preceding crop seasons happened without exception. Therefore, simply and objectively, the observation of a single monthly ONI or Niño–3.4 index value of + 0.7 °C in June (or earlier, of course) must be considered a primary criterion for warning of very early El Niño consolidation and consequent crop failures in this region.

Interestingly, corroborating with these results, another recent research (considering a time series in the period from 1950 to 2020) has stablished the simple criterion that a single ONI value of + 0.7 °C 'identifies a tipping point at which the El Niño event becomes locked in', meaning that an anomalous warming of sea surface temperatures in the Niño 3.4 region will surely continue. Once this threshold is reached, regions commonly affected by El Niño – such as the region under study – must be prepared to adapt and tackle the upcoming weather conditions (Glantz & Ramirez, 2020).

It is important to mention that the ONI values are available online only after each quarter (3 months period) has ended, i.e. around two months after the center of the quarter. ONI values may change up to two months after the initial 'real time' value is posted, since the value is precisely adjusted after some extra months of observations and calculations. Monthly Niño-3.4 Index values (which are used to calculate the more precise and more comparable ONI values) are available online earlier, in the following month (NOAA, 2021).

Another broader criterion for warning of early El Niño consolidation could be set as the occurrence of an ONI (or the monthly Niño–3.4 Index) value ≥ + 0.5 °C in July (or earlier, of course). Precisely, in one of the cases, 2010, the monthly Niño–3.4 index was actually still + 0.48 °C, while the ONI was finally calculated as + 0.5 °C. Within the 29 years under study, four (1998, 2003, 2010, 2016) out of five crop seasons with this characteristic (ONI ≥ +0.5 °C in July) presented lower yields, if compared to yields (Figure 2a) in all their immediate five preceding years. The exception (with a high yield) among these five crops seasons was 2005, which had a preceding crop season of neutral conditions and exceptional ascending yields. Therefore, with or without the risk of El Niño occurrence, it is strategic to monitor low and/or descending yields in the previous year (s) as indicators of (cumulative) unfavorable conditions for optimum plant metabolism and yield.

These results are in accordance with the fact already well described in the literature and revised in the introduction, that the yield in a certain crop season is strongly dependent not just on the conditions along its current crop season but is also dependent on the conditions during its previous one (s). Therefore, effects and consequences of the environmental conditions imposed cumulatively along the years on this perennial crop must be common to grapevines in different grape producing regions.

3.5 Mitigating crop failures

If an upcoming scenario of strong El Niño is forecasted early (during winter), several measures can be taken. The agrochemicals (such as systemic fungicides) necessary for tackling the adversities of fungal diseases in high humidity conditions and maintaining crop sanitary status can be purchased in advance and applied earlier. The financial planning of the companies can be better adjusted in advance. Agricultural insurance against crop failures can be suitably adjusted. Several other measures at field and crop management level are described next.

Canopy management is an important key to modulate light, temperature, air circulation and humidity inside the vineyard (Dry, 2000; Nachtigal & Mazzarolo, 2008). Since flowering, the removal of leaves and lateral shoots adjacent to bunches is an important strategy to improve air circulation, lowering humidity and optimizing the application of fungicides (Nachtigal & Mazzarolo, 2008). It also reduces shading, what increases the percentage of leaves with high photosynthetic rates, increasing the availability of photoassimilates and fruitfulness (Dry, 2000). Adjusting the doses of nitrogen (reducing total nitrogen or applying it in small doses) reduces vegetative vigor. High doses of nitrogen favor the development of mildew, the main grapevine disease occurring in Brazilian humid climates (Nachtigal & Mazzarolo, 2008).

In order to keep yields at an acceptable or 'safe' level, an important focus of attention must be fruitfulness. Keeping the physiological status of the vines at an optimum level is crucial, above all, during inflorescence induction and differentiation, what happens in the previous production cycle. It is relevant to note that, additionally to weather conditions, adequate levels of nutrients and water available in the soil are also crucial to maximize the number of inflorescence primordia (Guilpart *et al.*, 2014; Keller, 2020).

After addressing bud fruitfulness, the next factor to be taken into consideration is the number of fruitful buds kept at winter pruning. A simple and cheap strategy to mitigate lower yields caused by unfavorable spring weather (which lowers fruitset) would be possible until July–August (winter pruning): leaving more buds – and hence more inflorescences – at winter pruning in order to compensate the expected lower fruitset. Even though leaving more buds is generally considered undesirable in a normal/ideal condition, because leaving more shoots tend to result in more total biomass and create an imbalance between vegetative and reproductive growth, with larger shoot number per vine, individual shoots display lower vigor, creating a partial compensation at plant level. Invariably, the final net result is that, in vines bearing increased shoot number, total plant leaf area increases and plant total yield as well (Keller *et al.*, 2015). It is also worth to mention that, in vines with more buds, grape quality might also shift – but not necessarily negatively –, resulting eventually in fruitier and less vegetal wines with more intense red color in a red grape variety (Cabernet Sauvignon), for example (Chapman *et al.*, 2004; 2005).

In El Niño events, another strategy which could be combined to the previous ones is triggering a delay in bud phenological development. That could be achieved by, for example: employing later winter pruning and applying sodium alginate gel (Friend *et al.*, 2011); or employing other treatments, such as those with growth regulators which could finally delay flowering (as well as inflorescence induction and inflorescence differentiation), what normally happens in October–November, under the most adverse El Niño spring weather conditions.

CONCLUSIONS

The analysis of 29 crop cycles revealed patterns to partially explain grape yield oscillations in Santana do Livramento, Campanha Gaúcha, RS, Brazil. Relative yield deviations were calculated according to a fitted tendency line and showed correlations with the Oceanic Niño Index (ONI) 3–month running means centered in November (OND). La Niña events resulted in yield deviations close to or above the tendency line. El Niño events were linked to various yield results, including the lowest and the largest yields. The four largest crop failures happened in El Niño events, while three out of them happened in cases of early El Niño consolidation. The seven largest negative relative yield deviations – comprising four cases of early El Niño consolidation, one case of late El Niño consolidation and two cases of neutral years – were mostly linked to low yields and/or descending yields (negative yield shifts) in the previous year (s). The seven lowest yields were linked to El Niño, or descending or low yields in the previous year (s), or all these factors combined. Some simple criteria allowing early warning of conditions for crop failures were defined: Oceanic Niño Index (ONI) ≥ + 0.7 °C (or the monthly Niño–3.4 Index) in June (or earlier); or, more broadly, ONI ≥ + 0.5 °C (or the monthly Niño–3.4 Index) in July (or earlier); and/or low and/or descending yields in the previous year(s), even upon no risk of early El Niño consolidation during the next spring.

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REFERENCES

Alleweldt G & Ilter E (1969) Untersuchungen über die Beziehungen zwischen Blütenbildung und Triebwachstum bei Reben. Vitis, 8:286-313.

Anderson W, Seager R, Baethgen W & Cane M (2017) Agricultural and Forest Meteorology Crop production variability in North and South America forced by Southern Oscillation life-cycles of the El Niño. Agricultural and Forest Meteorology, 239:151-165.

Chapman DM, Roby G, Ebeler SE, Guinard JX & Matthews MA (2005) Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. Australian Journal of Grape and Wine Research, 11:339-347.

Chapman DM, Thorngate JH, Matthews MA, Guinard JX & Ebeler SE (2004) Yield Effects on 2-Methoxy-3-Isobutylpyrazine Concentration in Cabernet Sauvignon Using a Solid Phase Microextraction Gas Chromatography/Mass Spectrometry Method. Journal of Agricultural and Food Chemistry, 52:5431-5435.

Costa VB (2011) Efeito Das Condições Climáticas Na Fenologia Da Videira Européia Em Santana Do Livramento, Rio Grande Do Sul. Doctoral Thesis. Universidade Federal de Pelotas, Pelotas. 89p.

Cunha G, Dalmago G & Estefanel V (2001) El Niño Southern Oscillation Influences on Wheat Crop in Brazil. In: Bedö Z & Láng L (Eds.) Wheat in a Global Environment. Developments in Plant Breeding. Dordrecht, Springer. p.445-450.

Cunha GR (2001) El Niño southern oscillation and climate forecasts applied to crops management in southern Brazil. In: Cunha GR, Haas JC & Berlato MA (Eds.) Applications of climate forecasting for better decision-making processes in agriculture. Passo Fundo, Embrapa Trigo. p.181-201.

Dry PR (2000) Canopy management for fruitfulness. Australian Journal of Grape and Wine Research, 6:109-115.

Embrapa - Empresa Brasileira de Pesquisa Agropecuária (2020) Ciência ajuda vinho da Campanha Gaúcha a conquistar Indicação Geográfica. Available at: <https://www.embrapa.br/busca-de-noticias/-/noticia/52668635/ciencia-ajuda-vinho-da-campanha-gaucha-a-conquistar-indicacao-geografica>. Accessed on: May 27th, 2021.

Friend AP, Trought MCT, Stushnoff C & Wells GH (2011) Effect of delaying budburst on shoot development and yield of *Vitis vinifera* L. Chardonnay "Mendoza" after a spring freeze event. Australian Journal of Grape and Wine Research, 17:378-382.

Garrido L da R, Maia JDG, Ritschel PS & Gava R (2017) Manual de identificação das doenças abióticas da videira. Bento Gonçalves, Embrapa Uva e Vinho. 67p.

Glantz MH & Ramirez IJ (2020) Reviewing the Oceanic Niño Index (ONI) to Enhance Societal Readiness for El Niño's Impacts. International Journal of Disaster Risk Science, 11:394-403.

Guilpart N, Metay A & Gary C (2014) Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. European Journal of Agronomy, 54:09-20.

Huang B, Thorne PW, Banzon VF, Boyer T, Chepurin G, Lawrimore JH, Menne MJ, Smith TM, Vose RS & Zhang HM (2017) Extended reconstructed Sea surface temperature, Version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. Journal of Climate, 30:8179-8205.

Keller M & Koblet W (1995) Dry matter and leaf area partitioning, bud fertility and second season growth of Vitis vinifera L.: Responses to nitrogen supply and limiting irradiance. Vitis, 34:77-83.

Keller M (2020) The science of grapevines. London, Academic Press. 541p.

Keller M, Deyermond LS & Bondada BR (2015) Plant hydraulic conductance adapts to shoot number but limits shoot vigour in grapevines. Functional Plant Biology, 42:366-375.

Marques JR, Berlato MA & Janke A (2003) Probabilidade empírica de ocorrência de anomalia de precipitação pluvial sobre o Rio Grande do Sul condicionada a eventos El Niño - Oscilação Sul. In: XIII Congresso Brasileiro de Agrometeorologia, Santa Maria. Proceedings, SBA. p.1059-1060.

Matzenauer R, Radin B & Maluf JRT (2018) O fenômeno ENOS e o regime de chuvas no Rio Grande do Sul. Agrometeoros, 25:323-331.

Nachtigal JC & Mazzarolo A (2008) Uva : O produtor pergunta, a Embrapa responde. Brasília, Embrapa Informação Tecnológica. 202p.

Nicknich F, Cunha GR, Pires JL, Luiz ARM, Ughini SM, Hennerich J & Pasinato A (2005) Efeitos dos Fenômenos El Niño e La Niña no rendimento de grãos das prinipais culturas agrícolas do Rio Grande do Sul. Available at: <http://www.sbagro.org/files/biblioteca/1818.pdf>. Accessed on: March 08th, 2022.

NOAA - National Oceanic and Atmospheric Administration (2021) Cold & Warm Episodes by Season. Available at: <https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php>. Accessed on: April 30th, 2021.

Peel MC, Finlayson BL & McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences, 11:1633-1644.

Steinmetz S, De Assis FN & De Campos CJ (1999) Influência do El Niño Oscilação Sul (enos) sobre as condições climáticas, no período de outubro a março, na região de Pelotas-RS. Available at: <http://www.sbagro.org/files/biblioteca/457.pdf>. Accessed on: March 08th, 2022.

Timmermann A, An SI, Kug JS, Jin FF, Cai W, Capotondi A, Cobb K, Lengaigne M, McPhaden MJ, Stuecker MF, Stein K, Wittenberg AT, Yun KS, Bayr T, Chen HC, Chikamoto Y, Dewitte B, Dommenget D, Grothe P, Guilyardi E, Ham YG, Hayashi M, Ineson S, Kang D, Kim S, Kim WM, Lee JY, Li T, Luo JJ, McGregor S, Planton Y, Power S, Rashid H, Ren HL, Santoso A, Takahashi K, Todd A, Wang G, Wang G, Xie R, Yang WH, Yeh SW, Yoon J, Zeller E & Zhang X (2018) El Niño–Southern Oscillation complexity. Nature, 559:535-545.

Vasconcelos MC, Greven M, Winefield CS, Trought MCT & Raw V (2009) The Flowering Process of Vitis vinifera: A Review. American Journal of Enology and Viticulture, 60:411-434.