nature climate change

PERSPECTIVE

https://doi.org/10.1038/s41558-017-0016-6

From Pinot to Xinomavro in the world's future wine-growing regions

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Predicted impacts of climate change on crops—including yield declines and loss of conservation lands—could be mitigated by exploiting existing diversity within crops. Here we examine this possibility for wine grapes. Across 1,100 planted varieties, wine grapes possess tremendous diversity in traits that affect responses to climate, such as phenology and drought tolerance. Yet little of this diversity is exploited. Instead many countries plant 70–90% of total hectares with the same 12 varieties—representing 1% of total diversity. We outline these challenges, and highlight how altered planting practices and new initiatives could help the industry better adapt to continued climate change.

Climate change poses a major challenge to agriculture. New temperature and precipitation regimes, including new extremes in heat and drought[1], are dramatically changing the climate of most agricultural areas[2]. Even if warming is kept to the Paris Agreement target of "well below 2.0°C," almost all agricultural land will continue to experience large shifts in the local climate for decades to come. A major concern is that crop yields and quality will decline under these new regimes[3,4] unless producers and researchers alike can find ways to adapt crops to shifting climates. Among possible solutions[5,6], creating and exploiting diversity within crops to tolerate shifting climate has been a frontrunner[7]. By selecting certain genotypes of a crop that can withstand a region's new climate regime, growers could ideally continue to grow their current crop in their current location for many years to come.

Much research in using crop diversity to adapt to climate change has focused on developing diversity through breeding and genetic engineering[8,9]; yet this focus on 'new' diversity often leads to ignoring the existing diversity already found within many crops. This is unfortunate as creating new cultivars takes time (5–10 years for annual crops[10] and much longer for perennial crops[11]). Additionally, it may shift focus towards developing particular genotypes for the current climate, management and market conditions, while tacitly shifting focus away from conserving current diversity[12], which may harbor not just genotypes adapted to current conditions but also those adapted to future conditions as yet unknown. For example, today's standing diversity may include resistance to diseases currently unknown or considered unimportant, but which may be scourges in the future. Therefore, focusing on breeding and engineering diversity may actually reduce a crop's overall adaptive potential, at a time when climate change demands resiliency and sustainability[13].

Most crops harbor high diversity (for example, ref. [9]), through current or ancient varieties, and/or wild relatives[14,15]. Increasing interest in crop flexibility with climate change[13] has driven research into this often hidden diversity[16,17]. Such research has shown that local cultivars often outperform modern, widely planted cultivars, especially under periods of abiotic stress or increased disease[16], and has led to growing interest in better understanding, preserving and exploiting this diversity[14,17,18].

One major perennial crop that has high existing diversity and appears well adapted to handle shifting climate is common grapevine (*Vitis vinifera* subsp. *vinifera*). Currently at least 6,000 cultivated varieties of *V. vinifera* are planted across the globe for research or production[19] and this genotypic variation is linked to high variation in a number of characteristics, including cold tolerance, ripening time, and berry size[20,21]. This high variation in part drives grapes' high economic value. Wine grapes are the world's most valuable crop (http://faostat.fao.org/) and their value is closely tied to the quality of the wines ultimately produced. Such quality is linked to how well matched—in the selection of particular genotypes—wine grapes are to their climate conditions[5]. Indeed, the most common definition of *terroir* includes the matching of genotypic variation to the particular climate of a region and locality[22,23]. Wine grapes then are a particularly interesting case study for how to adapt agriculture to climate change[24].

Here we review the genotypic and phenotypic diversity related to climate—or climate diversity—currently present within *V. vinifera* wine grapes, and how this diversity may be best exploited for adapting to climate change. We start by examining where the center of this diversity lies globally and its implications for how wine grapes respond to climate—including warming, heat extremes, and drought. We then show how this climate diversity is currently used by the wine industry and how the lack of greater diversity in production today may limit producers' abilities to make high-quality wines in the future.

Though our focus here is one crop in particular, the challenges and benefits of exploiting existing climate diversity that we outline extend to many other crops. In particular, crops with high climate diversity (for example, those planted across diverse climates currently) may already possess the raw material for climate change adaptation with minimal investment and reliance on developing new varieties—if this diversity is properly maintained and used[18].

Global winegrape diversity

Wine grapes were cultivated from the wild grape species, *Vitis vinifera* subsp. *sylvestris*, somewhere in the Near East 8,000–10,000 years ago[20,25]. Across the globe today there are an estimated 6,000–10,000

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different genotypes (genetically unique variants) of cultivated *V. vinifera*, called varieties (or cultivars or *cépages*), such as Pinot Noir, Crimson Seedless, and Cabernet Sauvignon[20,26]. Numerous varieties are used for fruit consumption (that is, table grapes and raisins) but the majority are dedicated to wine production. In addition to the *V. vinifera* varieties, many interspecific hybrids are cultivated for cold and humid climates, or for disease resistance, but are generally considered lower quality. For many growers, producing high-quality grapes is the goal, as it can maximize the profit per hectare of planted land, despite sometimes being tied to lower yields (see Supplementary Materials).

The current number of commercial varieties (single species *V. vinifera* grown solely for wine production, and our focus here) is at least 1,100 (see Supplementary Materials). Within each winegrape variety growers have selected and propagated individuals with particular characteristics and labelled these different selections 'clones' (for example, Pinot Noir clone 828). Clones are propagated vegetatively and thus are usually genetically identical[27]; they represent small genetic differences within a variety, much smaller than differences that occur between varieties, which originate from sexual reproduction. We focus here on diversity at the variety level because it encompasses a greater phenotypic spectrum. Many aspects of the approach we describe, however, would apply to growers aiming to adapt to climate change through shifting clones[21], though the potential for adaptation may be more limited.

Variety diversity, climate diversity and plant traits

Over the millennia, winegrowers selected different varieties of wine grapes for unique phenotypic traits so that certain varieties were ideally matched to their local climates. Growers maintained particular varieties that produced regular yields and grapes that reached the appropriate balance of sugar, acid and other compounds to make high-quality, aromatic wines, discarding other varieties along the way[28]. Though the focus was likely on agronomic characteristics, growers were also inherently selecting for a suite of additional plant traits that made regular, high-quality yields from diverse climates possible.

The result are winegrape varieties today that show high diversity in their traits, especially those related to climate[24,29]. Varieties vary in their cold and heat tolerance[30], and how they respond to drought and water stress[20]. Perhaps the most noted and well-studied winegrape trait related to climate is phenology[31–33]. Different varieties of wine grapes tend to leaf (budbreak), flower, undergo veraison (a rapid increase in sugar in berries, generally accompanied by a change in berry colour and/or softness) and reach maturity at different times of the year, even when exposed to identical climates. This variation is extreme for wine grapes with budbreak varying over five weeks across varieties and maturity varying over 10 weeks (ref. [34]).

Phenological variation is critical to the large range of climates over which wine grapes grow and to the quality of grapes produced. High-quality wine grapes are produced by a careful matching of a grape's phenology to the local climate[35,36]: optimal varieties are those that mature close to the end of the growing season, allowing the critical period between veraison and maturity to be timed with the cooler temperatures of late summer[23,36]. Thus, in cooler locations, such as northern Europe, a variety that goes from budbreak to maturity in a short period of time, such as Riesling, Chardonnay or Pinot Noir is needed. In contrast, southern regions grow varieties that develop slowly over long, hot seasons[37]. Such varieties, including Monastrell (synonym of Mourvèdre) and Xinomavro (a late-ripening variety popular in Greece, but less popular internationally), cannot reach maturity without high heat accumulation.

Wine grapes' high diversity in phenology and other traits related to climate means that different varieties are expected to respond very differently to climate change[38]. As climates shift, winegrowers could rely on diverse varieties that can cope with new temperature and precipitation regimes through well-adapted traits. This requires, however, that diverse varieties be planted and appreciated by winegrowers and consumers alike.

How winegrape diversity is exploited globally

Although winegrape diversity is high, most diversity still remains effectively where it originated—in the Old World (Fig. 1). Almost all diversification has occurred in or near Europe (Fig. 2) and been exported to other regions. In comparison, extremely few varieties were created in other geographic regions with several notable exceptions (for example, Pinotage; see ref. [39]).

In place of in situ development of new varieties, New World wine regions (those outside Europe and the Middle East, such as Australia, Chile, South Africa, and the United States) imported Old World varieties to build their markets[40–43]. This reliance on Old World varieties was probably driven by the structure of the wine industry, cultural traditions, and consumer preferences. Like today, back when many new regions were established (for example, in

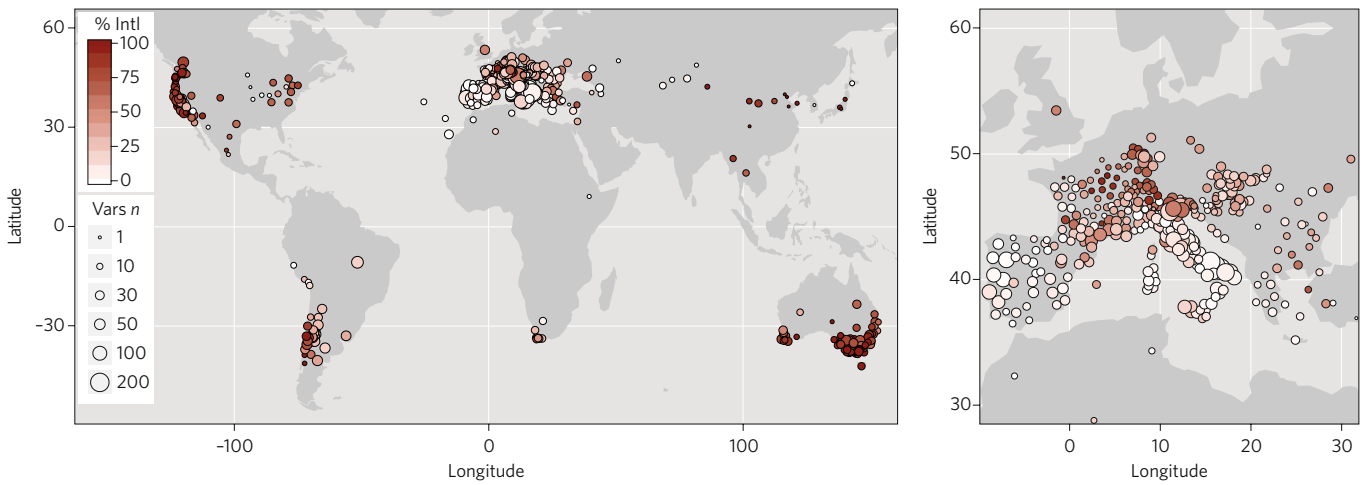

Fig. 1 | Current planted diversity of wine grapes. The number of varieties ('Vars *n*') by region, and the percentage of each region's hectares planted with common 12 varieties ('% Intl', called international varieties) varies across the globe, with Europe growing the greatest number of different varieties (largest circles) and New World wine regions growing the greatest proportion of international varieties (darkest circles). Data from ref. [47].

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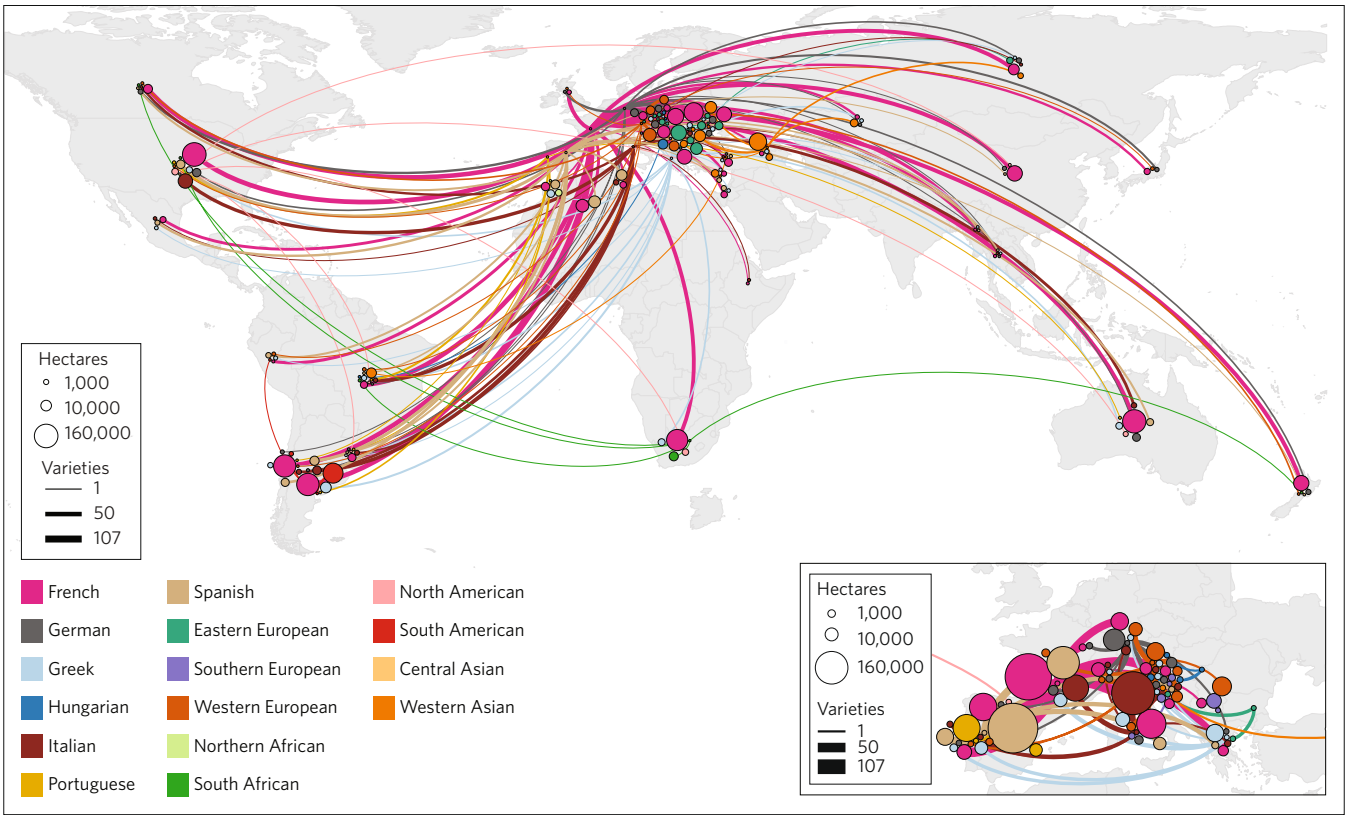

Fig. 2 | Origins of global winegrape production in 2010. The size of the circle represents the number of hectares planted from each origin of a variety, while the colour of the circle represents the origin of wine grapes planted there, and the width of the line represents the number of varieties planted from that origin. For visualization purposes, planted hectares in Europe are only shown in the inset map of Europe. Note that all wine grapes originate from the European *Vitis vinifera* subspecies *vinifera*; origin here is where the winegrape cross was made, thus Ruby Cabernet, a cross of two French grapes (Cabernet Sauvignon and Carignan) made in Davis, California would have a United States origin. Data from ref. [47] aggregated to country-level with circles set to the center of each country.

the 1550s for Chile and South Africa, and the late 1700s in California and Australia[20]), the breeding of new varieties that became popular with consumers was rare and attempts to use uncommon varieties generally failed[30]. This was the case in California, where early reliance on the widely planted Mission variety (currently known as Listan prieto, see ref. [44]) was thought to contribute to the low regard of American wines[41]. This led American winegrape producers to import other varieties from the Old World that were already popular and held in high regard there, and transformed the Californian market[41]. Unlike many traditional wine-growing areas in Europe (Fig. 3), most New World markets had—and have—no restrictions on which or how many varieties they could plant[45]. Yet across the globe wine-growing regions today contain only a small fraction of the variety diversity retained in the Old World, with the newest regions showing the lowest diversity (Fig. 1).

In addition to planting a small number of total varieties, newer wine-growing regions converged on focusing on a small set of varieties that became planted so commonly across such diverse geographies and climates that they have been termed 'international varieties' (*sensu*[46]). These twelve varieties—representing less than 1% of the total diversity of winegrape varieties grown today—cover more than 80% of the planted hectares in Australia and New Zealand, with other major regions following closely behind (for example, Chile at 78% and the United States at 70%). Furthermore, there's no evidence that this trend is abating. Instead, variety richness (total number) of wine grapes in production is declining overall[47] and international varieties appear to be on the rise across the globe (see Supplementary Figs. S4–S5). This domination of the market by only a sliver of the total diversity is common across crops (for example, banana and orange[48,49]).

Erosion in the diversity of wine grapes planted is probably due to a mix of factors. Globalization of the market is clearly a major driver (Fig. 2). Relatedly the historical shift from region-based labelling (for example, Bordeaux or Côtes du Rhône) to varietal labelling—started in California with the passage of a varietal labeling law in 1936 (ref. [50]) and followed by many other New World regions[51]—has focused consumers on identifying and buying a small number of varieties. Thus sellers may see a benefit in producing bottles of 100% Pinot Noir or Cabernet Sauvignon over blends of several varieties that would be better suited to their local climate. Regardless of the reason for declines in variety richness, the critical outcome is a winegrape crop that is more uniform across the globe and thus less resilient to environmental change.

Global diversity and diminished adaptive capacity

Wine producers' increasing reliance on a few major varieties translates into a global market that is investing in an increasingly limited portfolio at exactly the time when a large diversity of varieties is most needed. This narrow focus means a narrower range of critical traits related to climate, which in turn reduces the flexibility of most vineyards to adapt to climate change[13]. For example, across 115 varieties, we show high diversity in when different varieties reach maturity (Fig. 4). Considering only the widely planted international varieties, however, highlights how little—roughly half—of this spectrum most winegrowers currently exploit (Fig. 4). In particular, late-maturing varieties are

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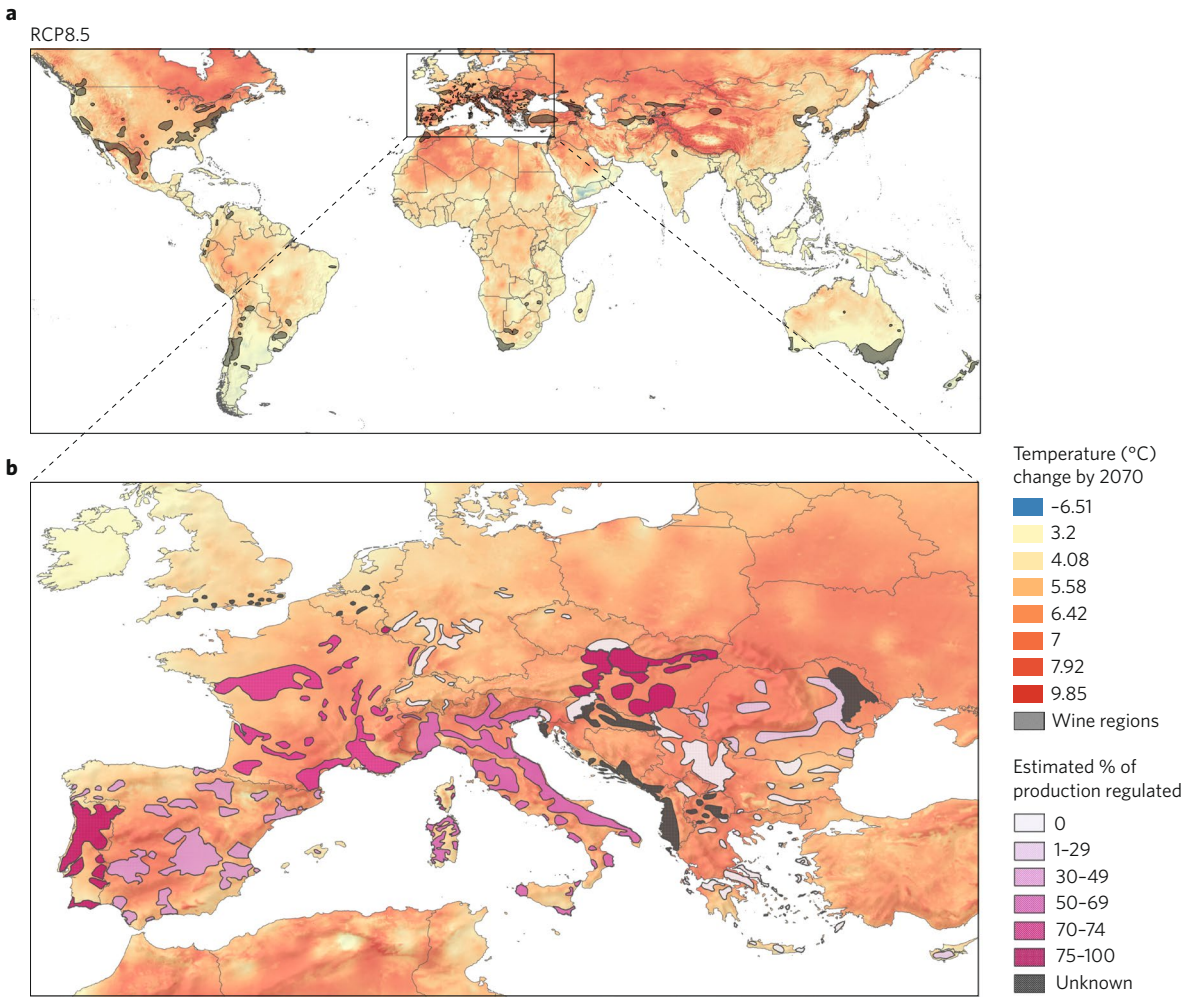

Fig. 3 | Growing regions projected temperature change (coloured by quantiles) and estimated varietal restrictions. a–b, A global map (**a**) and a European map (**b**) are coloured based on the projected changes in temperature during the growing season (March–September in the Northern Hemisphere, October–February in the Southern Hemisphere) by the year 2070 against 1970–2000 climate, as modeled by the general circulation model GFDL-CM3, and the high emissions scenario RCP8.5. Wine-growing regions are shaded in black within the global temperature change map (**a**). In the European map (**b**) they are shaded in a white to red colour depicting the estimated proportion of wine production under varietal restrictions, based on wines labelled by protected geographical indications (assessed at the country level). For more details on varietal restriction calculations and additional maps of climate change using alternative RCPs and climatic variables see Supplementary Materials and Figures S2–S3.

almost entirely excluded, even though late-maturing varieties are expected to be best suited for rising temperatures. These trends are seen in other traits as well. Shifting the focus from higher temperatures to increases in drought, Bota and colleagues[52] compared seven widely planted varieties to 16 more local (or 'indigenous'; see ref. [46]) varieties and found that local varieties spanned a much greater—and generally higher—range of leaf-level water use efficiency (Fig. 4). These results—though limited in their inference because they cover only two traits—suggest that wine grapes may harbor the necessary diversity to cope with a high diversity of climate regimes.

Yet current projections of future wine-growing regions with climate change suggest dramatic shifts in viticultural areas[53–55]. Unless emissions are strongly reduced, many warmer climate regions that currently grow grapes (for example, southern Europe or northwestern Australia) are expected to become too hot for high-quality grapes in the future (Fig. 3), while regions currently too cool will become new potential growing areas[54]. These models, however, have several major weaknesses: they generally forecast future wine regions based on current climate associations, and rarely include physiological mechanisms in their predictions (but see ref. [55]). Perhaps most importantly, they are built on the current wine-growing market, where few varieties with narrow climate diversity are widely planted across the globe. As such they underestimate, or ignore, the potential for wine-growing regions to stay in place, but shift the varieties planted.

Enhanced adaptive capacity through diversity

We have highlighted that many wine-growing regions have very low variety diversity, yet some Old World regions have retained a diversity of varieties despite a globalizing wine market (see southern Europe in Fig. 1). Successfully exploiting this diversity for climate change adaptation, however, requires major shifts by researchers, growers and consumers alike. Such a coordinated effort requires overcoming many hurdles, but offers far greater climate resiliency in return[13].

Exploit currently planted diversity. A first major need is greater research into how exploiting variety diversity alters projections of future wine-growing regions. Models that better incorporate variety diversity would move beyond current work outlining where the suitable and non-suitable habitat for wine grapes as a crop—writ

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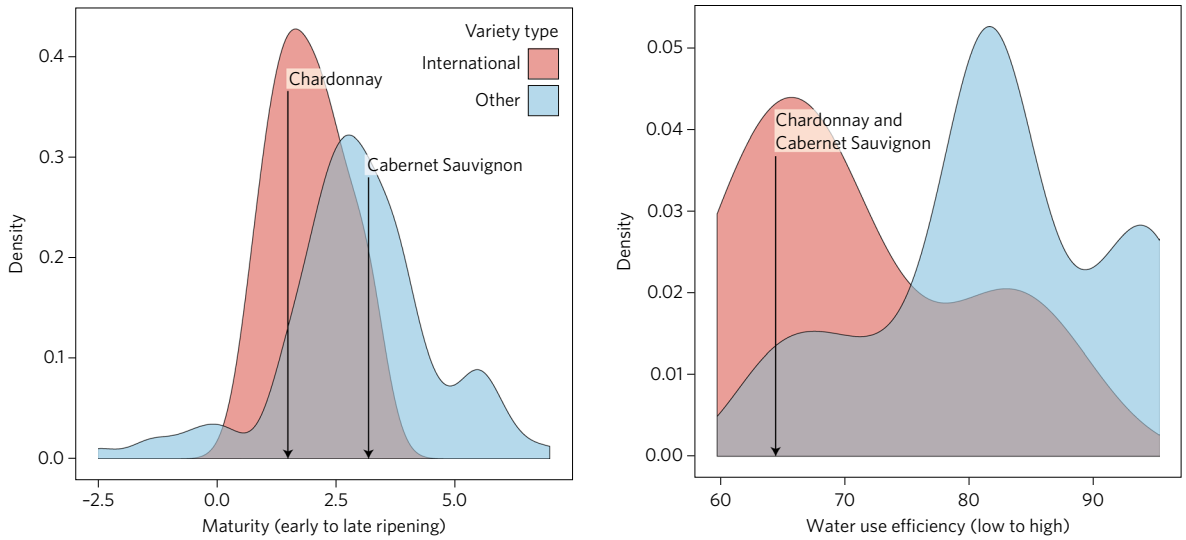

Fig. 4 | Variation across varieties in two traits relevant for climate change. Variation in the fruit ripening phenology (left) of the 12 international varieties versus a sample of 103 other varieties, maturity measured as weeks from when a reference variety (Chasselas) reached maturity (data from INRA Domaine de Vassal Grape Collection), and the leaf water use efficiency (ratio of water used versus lost, right) of seven international varieties versus 16 local varieties (from Balearic Islands, Spain, reported by ref. [52]). In many regions growers will need later-ripening grapes with higher water use efficiencies with climate change, yet the data here show that international varieties are skewed towards earlier ripening and lower water use efficiencies. Values for two of the most planted varieties—Chardonnay and Cabernet Sauvignon—are shown; on right they are shown by only one arrow because their values only differ by 0.1.

large—will be in the future by also predicting the turnover of varieties within regions. This would help growers understand how much shifting varieties may increase their options for adapting in place to climate change. Further, it would suggest which varieties may grow well in different regions in the future. Simple versions of these models could be developed soon[56,57], but more robust projections will require far more data on far more varieties. For example, process-based models predict yields and phenology[55], and can produce far more realistic projections, yet they are available for only a handful of varieties since such models require data on all four major phenological stages across a range of climates as well as basic estimates of physiological tolerances.

As a first step, researchers can make use of the diversity hidden in plain sight by collecting, analysing, and sharing existing data on a wider range of varieties. Researchers have tended to focus on a narrow set of widely grown varieties, resulting in a wealth of genotypic and phenotypic data on a few varieties (such as Syrah and Chardonnay) but very little to almost no data on most varieties. Basic phenological data are available for only 10% of the estimated 1,100 *V. vinifera* commercial varieties[57]. However, more data can be found in research collections where dozens to hundreds of varieties have been planted together to preserve and characterize diversity[58].

Observations of phenology, yield, and a suite of other traits across collections of different climate regimes would be tremendously useful in understanding how different varieties may fare with climate change. Such observations would provide robust estimates of varieties' traits, including how much they are controlled by genetic differences versus environmental (for example, climatic) factors. Understanding genetic versus environmental controls would importantly give information on the plasticity of these traits within varieties[59,60], and may highlight certain varieties that can maintain yield or quality characteristics across a variety of environmental conditions[61]. But simply collating data from different collections requires standardizing observation methods (for example, refs [62,63]), dealing with naming (synonymy) issues, and often overcoming government restrictions on sharing data.

A major source for data on diverse winegrape varieties outside research collections exists in the plantings of hundreds of thousands of vineyards around the world. Growers can play a major role in helping tackle the data challenge by sharing data they most probably already collect. Data on phenology each season and yields across varieties and blocks could rapidly improve predictions and projections if provided by even a small percentage of all growers. Vineyard-level weather data would also improve models by providing climate data matched spatially to the phenological data (for example, ref. [64]). Historical data would be particularly useful to fitting models as they would provide greater understanding of how climate has already shifted in a region and encompass a greater sweep of climate space. Though data sharing is not widespread among growers (or researchers) currently, many regions have cooperatives through which growers share knowledge regularly, and have shared data for climate-related initiatives (for example, ref. [65]).

Research on more varieties would provide one step in projecting future varieties across wine-growing regions, but research must also study a far greater diversity of traits across wine grapes. Projections would benefit greatly from estimates of heat, drought, humidity and cold tolerance: measurements that are currently available for almost no winegrape varieties. As warming brings more frequent and longer heat waves, heat tolerance will arguably be a critical predictor of which varieties to grow in many regions[29,66], analogous to what has been proposed for crops other than wine grapes[67]. Yet data on cold tolerance will also be crucial as climate change has already shifted frost regimes. In many areas of Europe, correlations between spring temperatures and frost events have shifted, such that earlier springs also include increased frost events, which produce wide-spread frost damage[68].

Beyond temperature, shifted precipitation regimes in the future will require understanding which varieties still produce regular yields of high-quality fruit under both higher and much lower amounts of precipitation[61]. Today's wine-growing regions (Fig. 3) cover areas projected to experience longer and more frequent droughts ([69,70]; see also Supplementary Fig. 3), as well as other areas where shifted storm patterns may bring higher quantities of rain at

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one time[71,72], which may in turn increase the risk of rot, mildew, and other fungal diseases favored by moist conditions[73,74].

Develop new trait-based modeling framework. Successful efforts to collect data on diverse traits across varieties and across varying environmental regimes will be of limited use without an effective method to synthesize findings. We argue that a trait-based approach could help researchers to identify a small set of measurable traits that predict a larger syndrome of how a variety responds to different environmental factors (Fig. 5). Such a trait-based framework has been useful in ecology, helping to identify repeating patterns across diverse species and environments[75]. The framework highlights common trade-offs between traits—often along an axis of easier-to-build (and therefore replace) tissues that are also competitively inferior under low resource conditions to tissues that are slower and more costly to build[75,76]. This fundamental trade-off appears to include a diversity of traits that predict how plants respond to the environment[77].

Given that such fundamental trade-offs also occur across winegrape varieties, then it should be possible to define a framework of trait syndromes for wine grapes (Fig. 5). Initial work would require measuring suites of traits related to how different varieties respond to the environment, many of which are time-intensive (for example, metrics of leaf and wood hydraulic design, heat and cold toler-

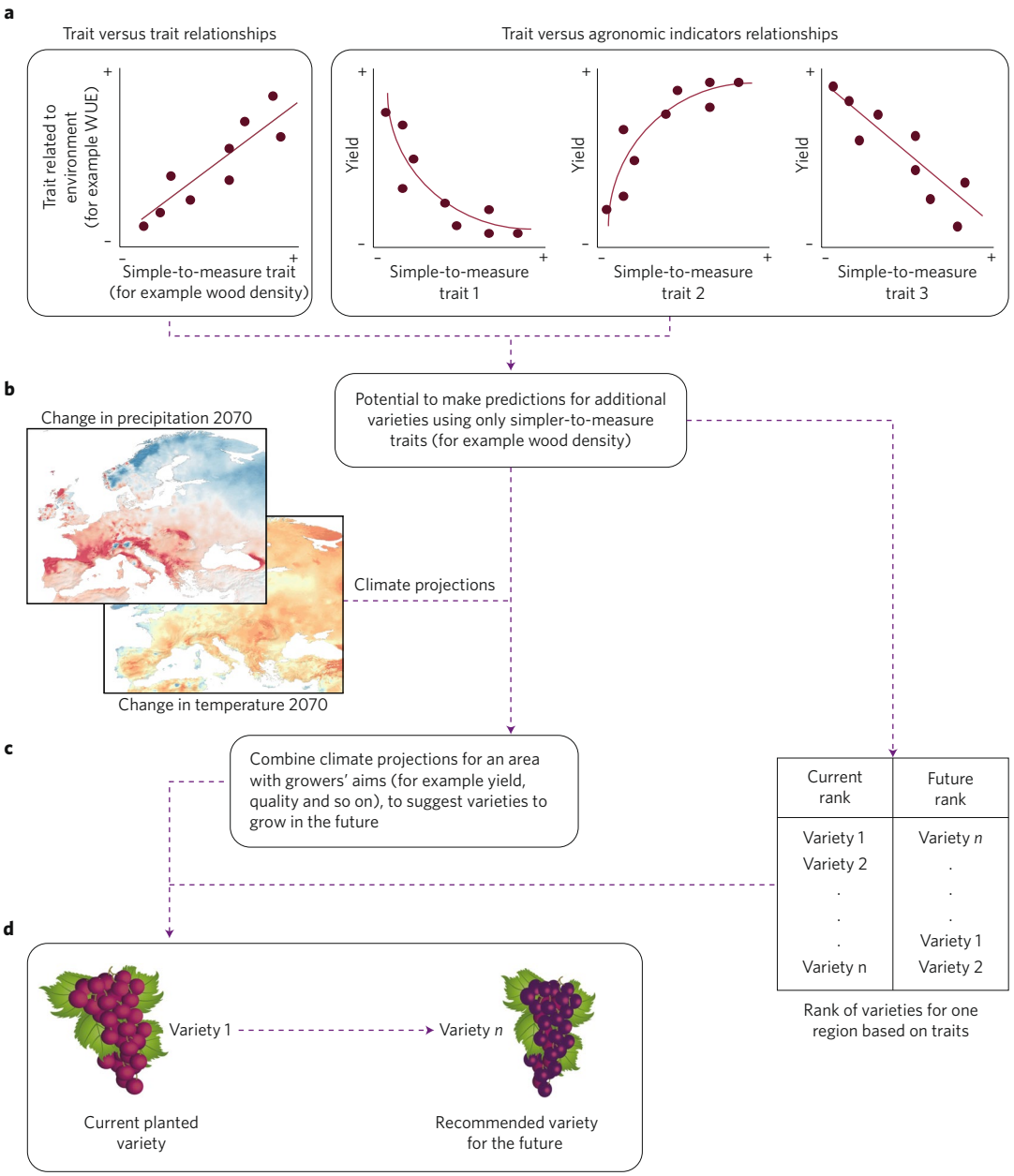

Fig. 5 | Trait-informed framework for selecting winegrape varieties in different regions under future climate regimes. a, Hypothetical relationships (left), measured across varieties (each dot is a different variety), between various simple-to-measure traits (for example wood density) versus more difficult-to-measure traits that are critically related to a variety's environmental response, such as water use efficiency (WUE). If useful correlations are found in **a** (left) the traits must then be correlated with important agronomic indicators, such as yield or quality (**a**, right). These relationships would ideally be assessed for each variety across differing climate regimes to better understand trait plasticity. **a**–**d**, Results from **a** would then be combined with projections (**b**) and growers' aims (**c**) to suggest future varieties (**d**).

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ances), yet others are quite simple (for example, wood density or specific leaf area). This framework could substantially reduce the effort needed to predict how most varieties respond to differing environmental factors as simple traits—found to relate to an entire syndrome of traits—could be measured to estimate where a variety falls within the framework.

Established plant trait trade-offs have been found both across and within species[78]; thus, it is highly plausible that these trade-offs also occur across wine grapes and other crops. However, millennia of artificial selection on wine grapes may have decoupled some trait–trait relationships. In such cases, identifying and understanding this decoupling may give breeders flexibility to select varieties with unique and agronomically valuable trait combinations. We suspect this may not be the case for many climate traits, however, as recent work highlights limits on the artificial selection of temperature traits[79].

Expand diversity research to commercial vineyards. Perhaps the most useful role that growers and technical institutes could play in improving variety projections would be planting and monitoring a diversity of varieties in their vineyards. This would not require a large-scale shift in a vineyard's planting but instead devoting a small number of rows or blocks to a diversity of varieties (as was commonly done in 'field plantings' in California, following Italian tradition, which increased wine complexity). Such plantings would provide data that could quickly increase the number of varieties for which researchers could build models. Additionally, for growers willing to open up their blocks to researchers, these variety diversity blocks could be prime locations for collecting additional trait data. Current catalogs of varieties provide some information on phenology, yield and pest and disease resistance, but variety diversity blocks could provide critical data on varieties' heat tolerances, drought resistance and other major climate-related traits.

Varieties for diversity blocks could be selected from those expected to be good candidates for planting in the vineyard in the next 20–30 years given climate projections. Therefore, growers would be providing useful data to researchers at the same time as they are testing out exactly how different varieties work in their blocks, providing themselves with useful information on which varieties to select to adapt the vineyard to climate change. Selecting which varieties to plant now for monitoring over the coming years or decades may be challenging for some growers. Though data are currently limited, we suggest growers could use a mix of several approaches for selecting these varieties. First, growers could look locally within their country or region for what varieties are commonly and widely planted in areas that match the expected future climate regime. In most cases this will be looking to local areas that are warmer and drier. In many New World regions, however, this set of varieties will still be very narrow. Therefore, growers should also consider importing lesser-known varieties from Old World regions that best match their expected future climate regime.

The power in such a design again comes from scale. To be useful to building variety projections and a trait framework, researchers would need replication of many varieties over the different climate regimes of different vineyards. Without this, varieties will be confounded with the vineyard's local climate and its management practices. We expect vineyards in one area would select many of the same varieties to monitor in diversity blocks, but over a larger area there would be an overlapping set of varieties measured over some range of environments. If growers from across a diversity of wine-growing areas, and at least a few vineyards within each area, invested in diversity blocks then data from the blocks could quickly and rapidly improve projections of ideal varieties for future climate regimes.

Shifting in place through diversity

It is clear that growers and researchers alike will have to invest in diversifying planted varieties in order to allow wine-growing regions to adapt in situ. Such adaptation in place has large advantages over maintaining the current focus on a few varieties, which would require investing in a wholescale shift of wine-growing regions to adapt to climate change.

Preserving current wine-growing regions through variety turnover with climate change will preserve areas of historical, cultural and economic importance. A number of European wine-growing regions are UNESCO World Heritage sites. In contrast, shifting wine-growing regions may lead to large destruction of natural areas and related loss of biodiversity as new tracts of lands are plowed under for new vineyards[54]. Furthermore, this expansion could continue for some time as wine-growing regions would need to continue shifting with continued climate change.

We argue that shifting regions would also result in lower quality wines as growers and winemakers must gain the experience to best manage the new conditions of their new agricultural land, which can take generations[5]. While climate change may alter the best-suited varieties for a local region, a number of other factors (for example, soil, daylength and so on) will remain unchanged. Shifting varieties—while it will take effort, new laws and regulations, and management changes—will maintain much more critical knowledge for producing high-quality wines than shifting wine-growing regions.

Planting new varieties will not be equally feasible in all regions and countries. In much of Europe, regulations restrict what varieties can be planted, and varietal labelling often relies on specific varieties being permanently tied to certain regions (Fig. 3 and Supplementary Materials). The opportunity to plant new varieties therefore resides in the hands of regional groups and governments that control labelling and importation rules. We argue these groups should work now to encourage variety diversity blocks by altering rules to allow in new varieties—perhaps as a start only in small quantities for the explicit purpose of small test blocks. They should further encourage these plantings by organizing efforts to store, manage and share the resulting data. Researchers in turn will need to support growers developing variety diversity blocks by providing the best possible climate projections for growers' regions, openly sharing data they collect from the diversity blocks, and making their results immediately useful to the growers.

Conclusions

Current and projected rates of climate change make investing in diversity and its by-products—adaptability, flexibility and resilience—critical to maintaining crop yields and quality. We have highlighted the role that climate diversity inherent in the different varieties of wine grapes could play in adaptation to climate change. Yet this adaptation will require growers and researchers to work together in gathering data and in building better projections of which varieties will be best for which regions in the future. With such data in hand, growers can begin to select the best varieties for their vineyards for the next generation of wine producers.

The approach we suggest—understanding and exploiting current climate diversity for adaptation—could apply to many other crops. In particular, crops where humans have historically planted diverse genotypes across large spatial sweeps—and thus across diverse climatic regions—may already have the capacity to adapt to shifting climate over time without moving across space. Such in-place adaptation would preserve local landscapes and local knowledge, as well as areas for conservation—as long as consumers are willing to accept new varieties from beloved regions.

Received: 2 December 2016; Accepted: 31 October 2017;
Published online: 2 January 2018

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Acknowledgements

Many thanks to C. Marchal and S. Dedet, who helped with data from INRA Domaine de Vassal Grape Collection (France), S. Schaffer-Morrison who helped build the dataset of geolocations of the world's wine-growing regions, E. Forrestel who helped format the crush report data from California, and to T. J. Davies, whose comments improved the manuscript.

Author contributions

All authors contributed ideas and edited the manuscript. In addition, E.M.W. wrote the manuscript, T.L. helped with data for Figs. 1,2 and 4. E.M.W. and I.M.-C. designed Figs. 3 and 5 together and EMW designed and produced Figs. 1,2 and 4.

Competing financial interests

The authors declare no competing financial interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-017-0016-6.

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