1. Story time: no grape needs heat in the ripening cycle (Happ 1999)
   1. Temps >40 degrees C over long periods of time🡪carbohydrate production stops🡪dead vines
   2. 20-45 degrees C likely ideal range of temp, but lower temps lower respiration demands and soil moisture depletion🡪more sustainable
      1. temps >30 degrees C noted as impairing function of vine
      2. growth maxed at 25 degrees C
      3. economy of effort
   3. post-veraison maturity independent of temp
2. Site and varietal choices for full flavor outcomes in a warm continent (Happ 2000)
   1. Lower temps leading up to maturation do not affect speed of maturation, but do enhance flavor retention
   2. Viticulture finds balance between thermal conditions favorable to flavor and limiting crop production
   3. Late-ripening grapes can make quality wines in warmer climates
   4. Minimizing heat loads maximizes wine quality
3. Heat Stress affects flowering, berry growth, sugar accumulation and photosynthesis of *Vitis vinifera* cv. Semillon grapevines grown in a controlled environment (Greer and Weston 2010)
   1. Methods sum
      1. 4 plants cv. Semillon placed in elevated temp regime (40/25 degrees C) for 4 days at start of each stage (flowering, fruit set, veraison, mid-ripening)
   2. Plants exposed at flowering lost all flowers
      1. Took a few weeks
      2. Inflorescence growth impeded
   3. Berries on vines heat treated
      1. at veraison and mid-ripening stopped growing and lost size (veraison only)
      2. fruit set to mid-ripening had lower yield due to fewer berries per bunch
   4. Photosynthesis rates reduced by heat treatment, plant recovered better if earlier in development
      1. at veraison: recovered by 4 days
      2. at mid-ripening: >12 days to recover
   5. Different varieties🡪different effects (Semillon shoot growth rate unaffected (but flowers sensitive), Chenin Blanc, Pinot Noir, and Carignane shoot growth slowed, Chardonnay shoot growth sped up)
4. Climate change, wine, and conservation (Hannah et al. 2013)
   1. Winegrowing land likely to decrease
      1. 25%-73% by 2050 (worse-case-scenario)
      2. 19%-62% by 2050 (better-case)
   2. New vineyards established at higher elevation, perhaps many areas currently naturally vegetated🡪loss of biodiversity
   3. Some vineyards have begun using adaptation strategies to help them remain where they are and to reduce their environmental impact
   4. Introducing new varieties better adapted to future climates could help limit need for wine growing regions to shift
5. Climate Induced Historic and Future Changes in Viticulture (Schultz and Jones 2010)
   1. Process-based phenology model used to reconstruct spring /summer temps from harvest dates in Burgundy 1370-2003
      1. Strong correlation between temp and harvest date
         1. Warmer periods🡪earlier harvest
         2. Colder periods🡪later harvest
   2. Viticulture generally between 12/13 degrees C and 22/24 degrees C
   3. Night temperatures rising more than day temperatures
   4. Wine regions likely to change by 0.2-0.6 degrees C per decade 2000-2049
   5. Shift towards poles🡪less land for winegrowing in the Southern Hemisphere
   6. Phenology has already significantly advanced in wine growing regions
      1. Currently at or near optimum growing season temp
   7. Upper suitability threshold for many varieties unknown
6. Phenological diversity provides opportunities for climate change adaptation in winegrapes (Wolkovich et al. 2017)
   1. Great diversity of phenology among varieties🡪chance for adaptation to climate change
      1. Change where certain varieties are grown, introduce varieties not commonly cultivated, or introduce genes better suited to changed climates
      2. Temp is biggest driver of phenology change
         1. Higher temp accelerates phenology
   2. Genetics+environment🡪phenology
      1. Continued studies to tease apart how
      2. Common gardens with as many varieties as possible in different climates
   3. General winegrapes/climate change
      1. Advance in timing of leafout/flowering in plant species = 4-6 days/degrees C
         1. 2-5 days per decade in last 30-40 years
      2. Global wine market valued at 30 billion euros
      3. Clonally propagated🡪little genetic change
      4. Timing of stages can vary by 3-6 weeks across different varieties
      5. Cooler regions tend to plant early maturing varieties, opposite is true of warm regions
      6. Currently =< 100 varieties have data beyond harvest dates
      7. Collect pheno data every 1-3 days
      8. Quality emphasized over yield by growers
   4. Fig. 2 good to show variety variation and explanation of stages
7. From Pinot to Xinomavro in the world’s future winegrowing regions (Wolkovich et al. 2017)
   1. Key to best-case-scenario for viticulture industry is to introduce new varieties with the traits to survive altered climate where vineyards already exist
      1. Test plots can be used to find best match for future climate
         1. Focus on local varieties
      2. Regulating bodies should act to allow change in laws for new varieties in new regions
      3. Avoid infringing upon current conserved areas to expand winegrowing region
      4. Preserve knowledge of current vineyard land
   2. Process-based models best option for predicting yield/phenology
      1. Need much more data from greater number of varieties in more diverse range of climates
      2. Focus on heat, drought, humidity, and cold tolerance
      3. Trait-based method ideal
   3. Worldwide winegrape diversity declining
      1. Almost all diversification originated in Europe
      2. Other wine growing regions focus on a limited number of varieties transplanted from Europe (<1% genetic diversity of all winegrapes)
      3. Even in Europe, local varieties are being replaced with international varieties
   4. General winegrape/climate change
      1. 1100 commercial winegrape varieties V. vinifera
      2. 6000 cultivated varieties worldwide
      3. Clones propagated vegetatively
      4. Budbreak timing can vary over 5 weeks across varieties
      5. Maturity can vary by over 10 weeks
8. Climate change decouples drought from early wine grape harvests in France (Cook and Wolkovich 2016)
   1. High temps and drought historically came together
      1. Due to effects on phenology
      2. Warmer temps🡪early harvests (-6 days/ degree C)
         1. Temp most critical factor
      3. Wetter conditions🡪later harvests (+0.07 days/mm, +1.68 days/PDSI)
   2. 1981-2007 data shows drought no longer necessary for high heat to hasten harvest – insignificant relationship
      1. Impacts fruit maturation directly (acid production) and indirectly (soil moisture/air temp)
   3. Harvest dates moving earlier in last half 20th century
      1. More than 1 standard deviation
      2. Temps now high enough to make harvests earlier without drought
9. Temperature-dependent responses of the berry development process of three grapevine (*Vitis vinifera*) cultivars (Greer and Weedon 2014)
   1. Methods sum
      1. 15 Chardonnay, 15 Merlot, 10 Semillon
      2. Randomly placed in elevated temperature regime post veraison
         1. 20/14, 25/17.5, 30/21, 35/24.5, 40/28 degrees C
      3. Length of time in heat treatment depended on severity
         1. 6 days at 40 C
         2. 12 days at 35 C
         3. 18 days in all other treatments
      4. measured berry size, berry dry weight, and sugar accumulation
   2. Chardonnay likely cool season cultivar
   3. Semillon and Merlot most likely warm season cultivar
10. Effects of temperature and light (before and after budburst) on inflorescence morphology and flower number of Chardonnay grapevines (*Vitis vinifera* L.) (Petrie and Clingeleffer 2004)
    1. Methods sum
       1. In vineyard
       2. Mini chambers placed around buds
          1. Chambers open (increases temp—10-14 degrees C higher) or closed
       3. Levels of shading
          1. Foil to increase sunlight, clear, and shading to decrease sunlight
       4. Treatments applied for a duration of 14 days before budburst for one set and duration of 13 days after budburst for another
       5. Chardonnay
          1. 10 replicate vines in pre-budburst
          2. 9 replicate vines in post-budburst
    2. Higher temperature decreases number of flowers
       1. More pronounced pre-budburst (17% reduction)
          1. Shading decreased temp and caused 13% increase in number of flowers
          2. Flower development more sensitive pre-budburst?
          3. Reduction in flower number of 32.6-24.2 flowers per degree C
       2. Post-budburst, number of flowers decreased significantly for heat-treated buds, as well
          1. Shading had no effect
    3. Figure 2 shows pretty clean relationship between temp and flowers per inflor
11. Influence of Climate, Soil, and Cultivar on Terroir (van Leeuwen et al 2004)
    1. Methods sum
       1. Vineyard plots (“homogenous climate zone”)
       2. Merlot, Cabernet Sauvignon, and Cabernet franc
       3. Components of terroir
          1. Three soil types (gravelly-sandy, heavy clay, sandy-clay)
          2. Climate (min and max temp, sunlight hours, degree days, ET, rainfall, and water balance)
          3. Cultivar