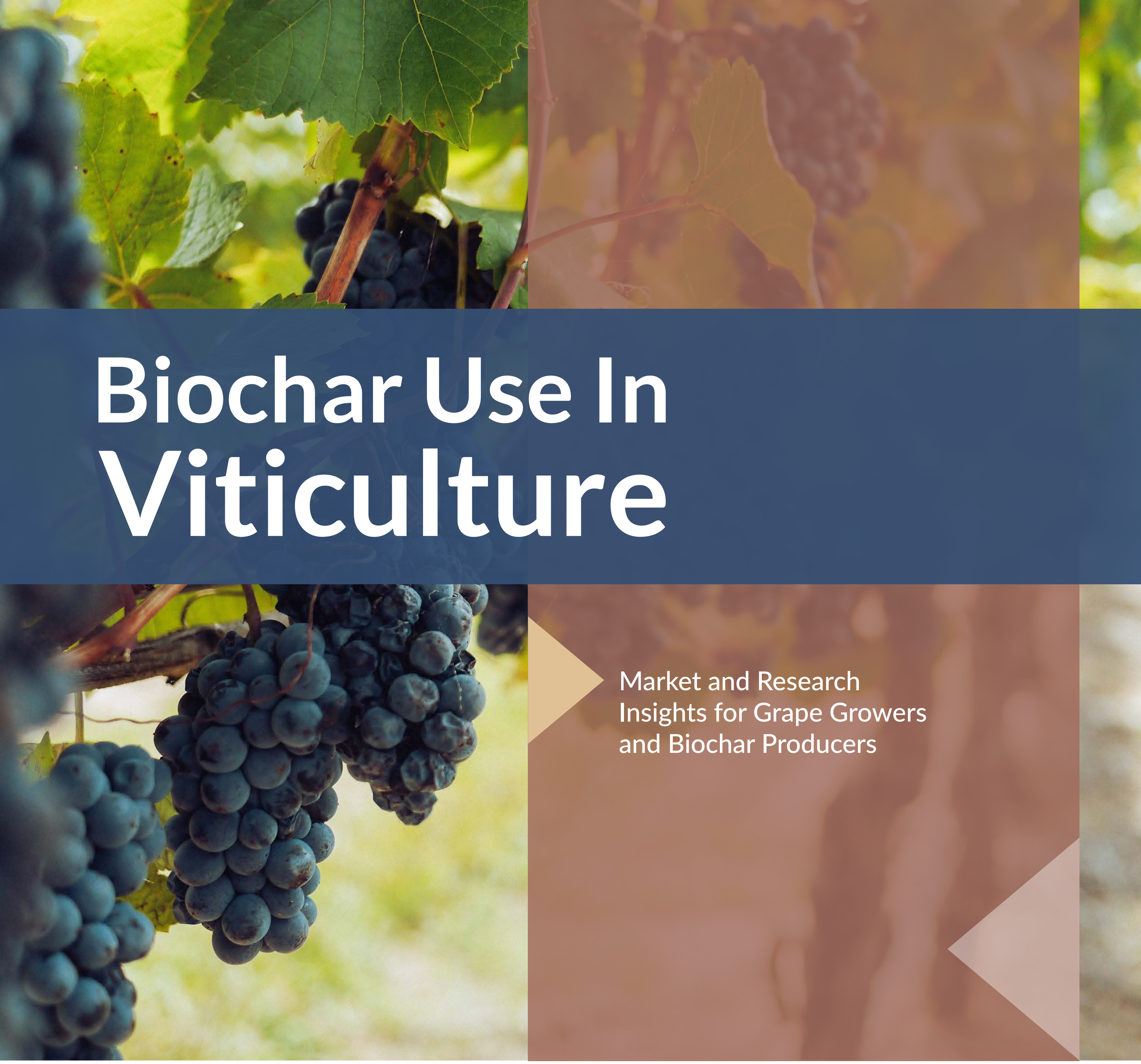

Biochar Use In Viticulture

Market and Research Insights for Grape Growers and Biochar Producers

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Executive Summary

Biochar has been successfully used in viticulture to boost productivity through improved plant and soil health without negative effects to the grape or wine flavor. There is a large body of research supporting the application of biochar in viticulture specifically, as well as in soils and compost. A dozen of the most recent and relevant are highlighted in support of biochar's use in viticulture.

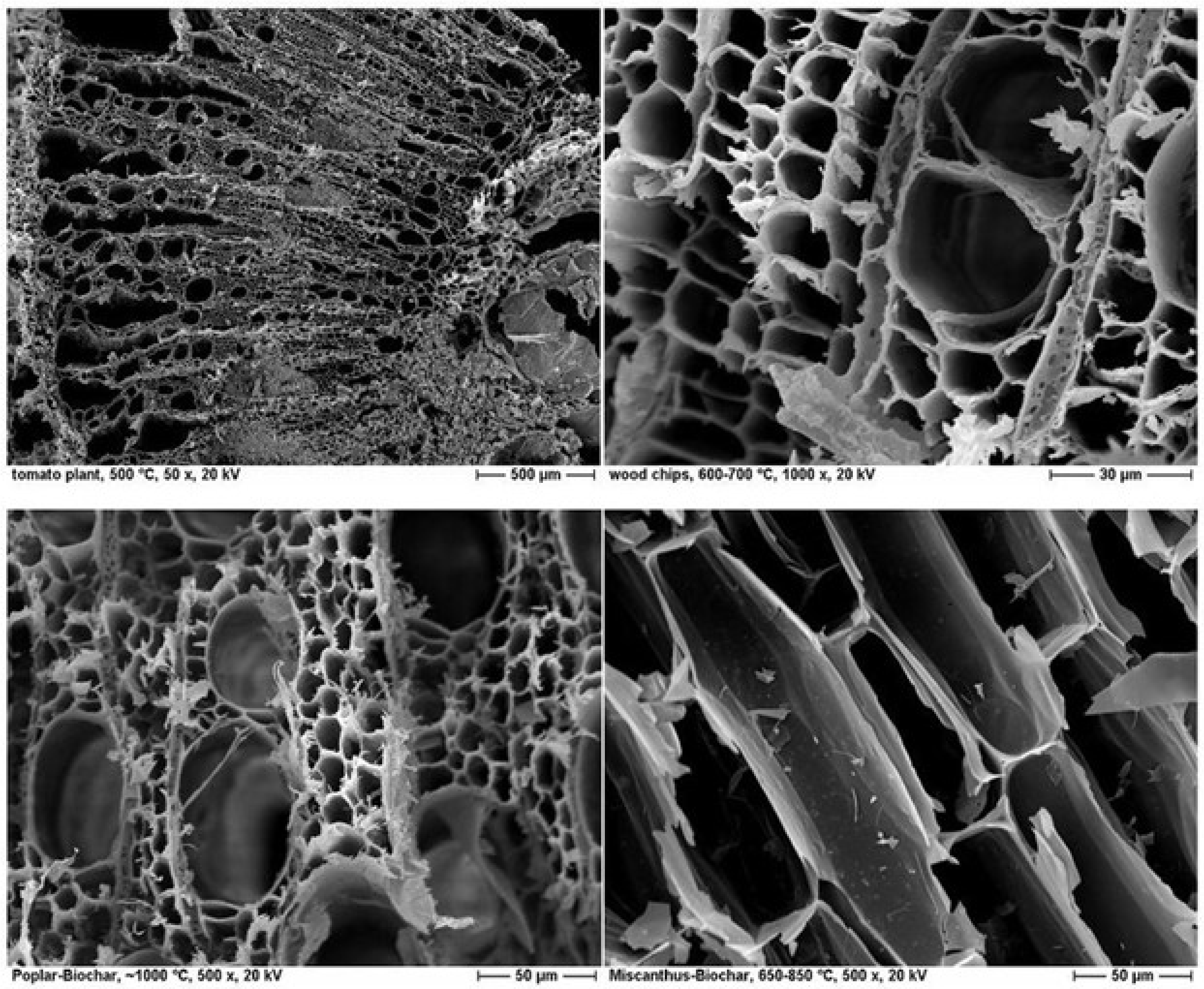
While there are some caveats to be considered when applying biochar, if it's matched appropriately to the soils at establishment, growers are seeing a 2 to 3 harvest payback. The growing need for improved water management is one of the prime benefits seen in vineyards, and that need is expected to intensify as a changing climate affects water availability further. An additional benefit to an investment in biochar is its longevity—measured in decades to millennia—which also opens the potential for economic benefit from the developing carbon credit markets.

For biochar producers, there are almost a million acres of grapes in the US, offering the industry a sizable market. A one percent market penetration would require about 10,000 tons of biochar annually and though the bulk of grapes grown in the US are along the West Coast, the viticulture market provides opportunity in almost every state.

Introduction and Overview

Biochar is the product of heating organic feedstocks[1] in a low oxygen environment, a process called pyrolysis. Processing temperatures for biochar range from 400 to 1000C and, depending on the specific feedstock, temperatures, and post processing, will produce a granular high-carbon product. Biochar's primary characteristic is its large surface area, which can be used for storing water, nutrients, mycorrhizae, and other soil biota within its long-lasting[2] carbon matrix. This will be covered more in Section 1.

Figure 1. Biochar production and application supply chain (adapted from: Anderson et al. 2017. Chapter 2 in Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation, Cambridge University Press.)



Glaser, B, Wiedner, K., Biochar-Fungi Interactions in Soils; February 2013; DOI: 10.1201/b14585-4

Biochar has proven beneficial to viticulture in a number of ways however, like any soil amendment, its characteristics have to be matched to the needs of the soil. This report explores the science and practical experiences which support the claims of those benefits, looks at the opportunities for viticulturalists specifically and offers biochar producers guidance to serve the market effectively. Below is an overview of the four sections of this document, each of which has been written to stand-alone but with interconnecting use of the research findings in Section 1 and the practical experiences in Section 3:

Section 1. The Science: Research Supporting Biochar's use in Viticulture

Most of the research presented here is relatively current-in the 5 years prior to this report's release. There are a few references to foundational work which is still relevant but, by-and-large, this report focuses on recent and/or ongoing exploration of viticultural biochar use. To offer a holistic perspective there are two studies included in the research reviews which look at potentially negative effects of biochar.

Section 2. For Grape Growers: Using Biochar in Viticulture

Section 2 is for vintners. It provides an overview of the opportunities and considerations for grape growers to use biochar at-scale—and how to do it effectively.

Section 3. Growers' Experiences with Biochar In-the-Vineyard

This section looks at field trials and personal experiences: the application and "real world" validation of formal research (i.e., "the science") by individual vintner's experimentation. Although these may lack the rigor of academic research, they demonstrate what's feasible in real-world conditions and in a production setting.

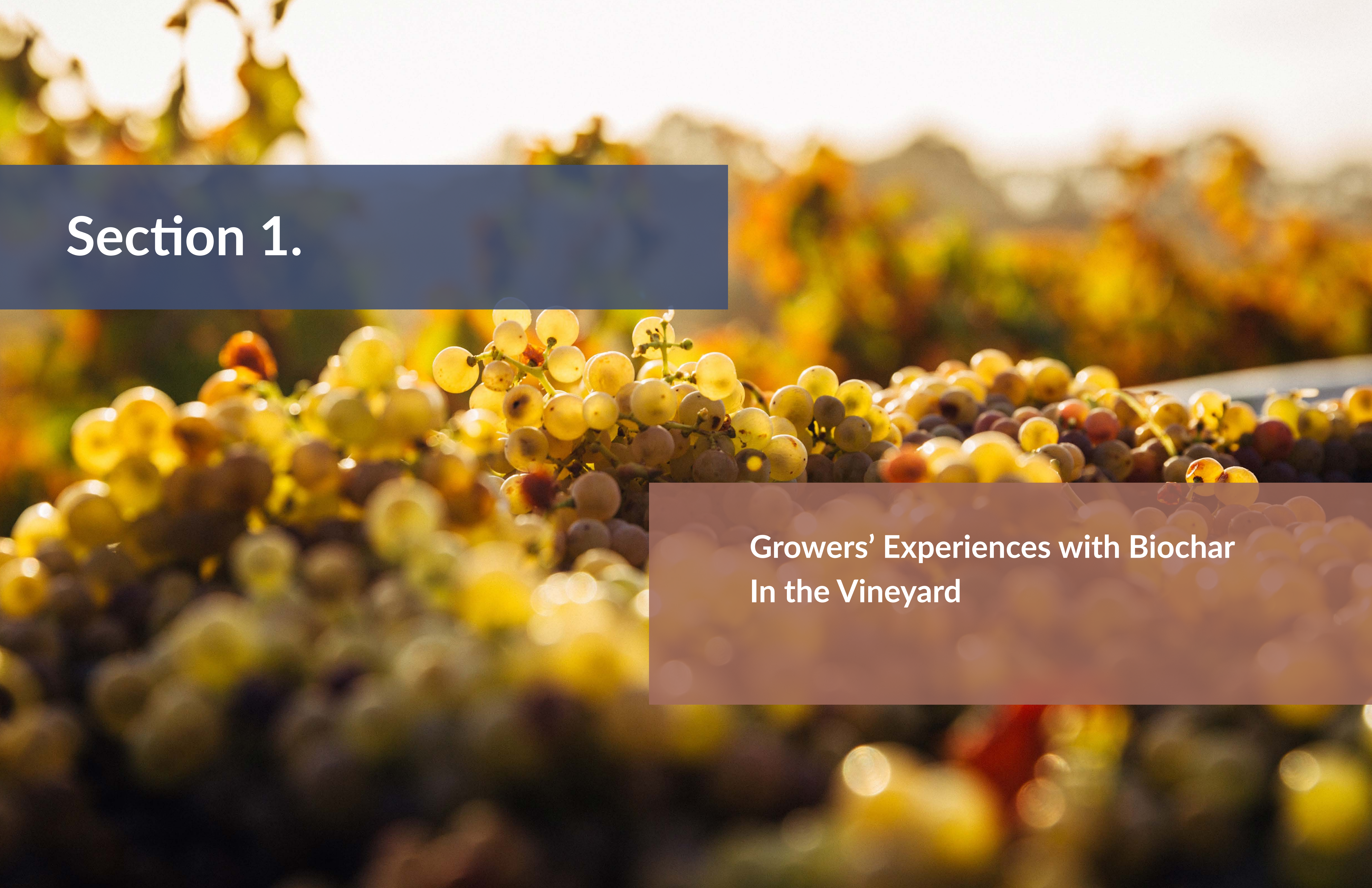
Section 4. For Biochar Producers: Market Potential for Biochar in the Grape Industry

The last section is for biochar producers. It provides guidance for supplying biochar to the viticulture industry and developing effective marketing.

[1]Feedstocks range from woody to grassy, bones, manure, livestock litters, and other inputs to create specialized chars.
[2]Biochar is considered a stable carbon product for decades to millennia.

Section 1.

Growers' Experiences with Biochar In the Vineyard



Section 1. The Science: Research Supporting Biochar's use in Viticulture

Research has demonstrated that certain types of biochar can be useful in a variety of agricultural settings (i.e., different soil types, grape varieties, and treatment regimens). One of the most often cited benefits, beyond an increase in soil carbon, is its ability to improve water management. The specific effects are closely tied to the native soil characteristics and the specific biochar characteristics, but nutrient leveling and increased soil biota activity are common. The following articles highlight research which support these benefits of biochar:

- Water retention: 1, 3, 4, 6, 7, 8, 10, 12
- Increase Soil Carbon: 1, 2, 4, 5, 6, 8, 9, 10, 12
- Nutrient release leveling: 2, 4, 7, 9, 12
- Soil structure management: 1, 3, 4, 6, 7, 8, 12
- Soil Biota improvement: 4, 7, 11
- Soil contamination mitigation: 5, 7, 11
- Pruning and marc disposal: 4, 5, 11
- Increased yields: 1, 2, 4, 8, 9, 10, 12
- No effect on wine taste: 4, 10, 12
- Article 13 is a study of potential adverse effects of biochar

1. [3]A multi-year field experiment was performed in a Tuscany vineyard, consisting of 15 four vineyard rows and three inter-row plots, in an agricultural soil classified as sandy–clay–loam (70% sand, 15% silt, and 15% clay.) The 2015 publication of the research results included that after applying 33 dry metric tons of biochar per hectare (14.7 tons per acre (TPA)), while the cumulated rainfall increased during the research period there was little reduction in the soil carbon, indicating that a substantial part of carbon from biochar is resistant to migration processes. Grape productivity increased (up to 66%) in all the harvests following biochar amendment, even as the fruit quality remained unaffected.[4] The increased yields were likely to be due to the enhanced soil water content and plant-available water in the treated soils in comparison to the control soil.

2. In a 2017 to 2019 Washington State University study[5] looking at applications of compost where the biochar was mixed in prior to composting or the biochar was mixed into the finished compost before application to a variety of crops.

   Crop yield and soil health attributes were generally affected, and in many cases, significantly so, by the co-compost and compost plus biochar treatments. Co-compost and the compost plus biochar were typically observed to affect soil physicochemical properties beneficially, except in the case of bulk density. Our results suggest that blending compost with biochar optimizes the physical and chemical properties of each, but that this effect is somewhat dependent upon the native soil and crop.[6]

   While the project found generally beneficial results, but their cautionary notes are worth noting:

   The use of biochar as a soil amendment in cropping systems may be beneficial, but its use, and the intent of its use, need to be carefully considered and clearly defined. The differences we observed between biochar products (i.e., co-composted biochar or biochar alone) warrant this consideration, as growers using one or the other will likely see drastic differences in performance, and so, expectations for yield and soil responses should be appropriate to the product. Finally, it is important to note that data presented here is from one growing season which makes it difficult to draw conclusions and make confident statements. It should also be noted that because the characteristics of the biochar and compost impact chemical and biological processes, the use of different types of biochar or compost in these studies would be expected to yield different results.

3. In a study[7] looking at the pyrolysis temperature of biochar, specifically how it affects water holding capacity, the following highlights were presented:

   - "Hydrophobicity was found in biochar from both feedstocks pyrolyzed at 400 °C, but not at higher temperatures." One reviewer[8] questioned whether the hydrophobic condition persists and noted, in their experience it did not. "I think biochar can be used to the advantage of the applying manager on the right soils. When biochar is placed into solution and applied to a well drained soil. The biochar is entrained by the water into the soil profile. A test I conducted in an excessively well drained pumice soil, it retained 99% of a fine particle biochar application within the upper 12" of the soil profile (i.e. the rooting zone). This test also showed a slower draining of the soil [water] column from the addition of the biochar.
   - "Available water content (AWC) of biochar increased with increasing pyrolysis temperatures, with optimal results obtained from grapevine cane at a pyrolysis temperature of 700 °C, which had an AWC 23% higher than a typical clay type soil."
   - "Pure biochars were superior in water retention performance to typical sandy soils, and so biochar amendment of these soil types may improve water holding"
   - "Vineyard-derived biochar produced onsite therefore has the benefit of improving viticultural water efficiency without the need to transport biochar long distances, thereby increasing the economic potential"
   - "Despite the similar initial carbon content of the two waste biomasses, grapevine cane consistently had a higher carbon content than the stalks at the same pyrolysis temperature. In both feedstock types, carbon content increased as pyrolysis temperature increased"

[3]Fate of Soil Organic Carbon and Polycyclic Aromatic Hydrocarbons in a Vineyard Soil Treated with Biochar; A. Rombolà, W. Meredith, C. Snape, S. Baronti, L. Genesio, F. Vaccari, F. Miglietta, and D. Fabbri; Environmental Science & Technology 2015 49 (18), 11037-11044 DOI: 10.1021/acs.est.5b02562

[4]Multiple studies have found increased yields with no effect on wine quality or taste.

[5]Integrating Compost and Biochar for Improved Air Quality, Crop Yield, and Soil Health; D. Gang, D. Collins, T. Jobson, S. Seefeldt, A. Berim, N. Stacey, N. Khosravi, W. Hoashi-Erhardt; A report for The Waste to Fuels Technology Partnership 2017-2019 Biennium: Advancing Organics Management in Washington State; Sept 2019

[6]In general, the better the native soil, the less effect biochar will have.

[7]Pyrolysis Temperature Effects on Biochar–Water Interactions and Application for Improved Water Holding Capacity in Vineyard Soils; J. Marshall, R. Muhlack, B. Morton, L. Dunnigan, D. Chittleborough, C. Kwong; Soil Syst. 2019, 3(2), 27; https://doi.org/10.3390/soilsystems3020027

[8]Jim Archuleta, Soil Scientist with the US Forest Service

4. In an October 2020 article in Grapegrower & Winemaker Magazine[9], is based on field trials in a New Zealand (NZ) vineyard at Mt. Difficulty, in South Australia at Temple Bruer vineyard, and research done at the University of Adelaide. There were a number of relevant findings shared with the readers, among which:

   - "Biochar must be mixed with a nutrient dense solution such as compost or manure before application."
   - "Dicey [NZ] buries the biochar and compost mixture at a depth of around 40cm below most grass and weed roots, in a ratio of 1:10 biochar to compost, at 10 tonnes per hectare. It is also applied as a 50cm wide, up to 25cm high mulch strip beneath the vines, at 20 tonnes per hectare. The intent of the second application is two-fold; biochar acts as a weed suppressant and it maximises the potential CEC [Cation Exchange Capacity, potential bonding of nutrients and minerals to the biochar surface] of the soil."
   - "The other benefit studied as part of the trial was the water holding capability of biochar as a means of managing irrigation demand. The porous structure of biochar aids water retention and data from trials in European vineyards estimate biochar is capable of retaining up to five times its weight in water. At the conclusion of the Central Otago [NZ] trial, an increase in plant available water of 30% was recorded for the biochar application."
   - "The water retention capabilities of biochar have previously been studied at The University of Adelaide [Article 2, above.] The results, published in 2019, showed increased available water content in biochar burned at higher temperatures. Grapevine canes burned at 700˚C produced biochar with available water content 23% higher than a typical clay soil. If increased access to water can be obtained beneath the soil using biochar, the demand for irrigation and the potential leaching of nutrients at the site of irrigation are both reduced, lowering irrigation costs and optimising water management."
   - "The results were published in June 2020 and the project was led by Professor Jim R. Jones, who said, "biochar delivers far-and-away the best environmental outcome. Going down the biochar route means the industry potentially has the opportunity to offset the emissions from all other parts of the production and supply chain."

   Of note is that, for this study, the biochar for the trials was created in the vineyard using a trailer mounted Kon Tiki-style Kiln[10] , using grape prunings as feedstock. The Kon Tiki Kiln is considered a low-tech method of pyrolysis and is mentioned as an example of a low cost option for vineyards to produce their own biochar.

5. One aspect of the wine industry that the table grape and raisin sectors don't have to deal with is the marc (also called pomace)—the leftovers from the wine pressing process the skins, pulp, seeds, and stems of the fruit. A NZ study looked at direct application, drying, composting, combusting, or pyrolyzing the marc[11]. It concluded combusting, gasification, or pyrolyzing made the most economic and environmental sense, with pyrolysis products the most salable; from the report:

   "Pyrolysis for charcoal/biochar. Three versions of this option are presented which go from very profitable to costly. Pyrolysis allows the opportunity for the most side stream products. This approach progresses the wine industry towards the wider bio-refining concept, where many opportunities for value adding become integrated. **The most advantageous approach with biochar/charcoal may be a combination of the three versions, to achieve both a favorable overall carbon footprint and achieve profitability.** The three options researched are:

   - Biochar for soil addition
   - Charcoal heating pellets
   - Activated charcoal

   Option 1 provides by far the best environmental outcome with carbon sequestered permanently into the soil. This net draw-down of atmospheric carbon can be used to balance net emissions in other parts of the winemaking process, and it is also likely to have the largest sustainability benefit by adding value to the wine product in environmentally sensitive markets. The second option would require a lower-tech processing capability, but a need for pelletizing equipment and there would be no carbon capture potential with this option. The third option requires more sophisticated processing equipment, but this study showed the product is a highly profitable product. It should be noted this economic feasibility did not explore the various technologies to generate other co-products (i.e., syngas or pyroligneous acid)."

6. The Natural Resources Conservation Service (NRCS) promotes the increase in soil organic matter (SOM)[12]. It's been calculated that a 1% increase in SOM can increase water holding capacity by 25,000g/ac. Biochar is a recalcitrant form of SOM, less likely to decompose than green manure or mulches.

   Note[13] : if water capacity is increased one should not assume all of the new capacity is plant available; a percentage is lost to evapotranspiration, to soil drying (evaporation), and some is held in the soil's capillary fringe so tightly it neither dries nor is taken up by plants. In the latter we gain an opportunity: with Climate Change we expect a change from precipitation as snow to rain. Increasing SOM can benefit crops with more capacity within the capillary fringe. In the next water year, the new water inputs allow the soil to reach saturation faster. In year two, this new water is then influenced by gravity once the water column in the soil builds hydraulic head, drawing water toward creeks/streams/rivers/aquifers.

7. A meta-study[14], which screened about 15 years of published research and gathered data on the use of phytosanitary products and mechanization in vineyards ranked viticultural production systems and practices according to their impact on soil biodiversity using 50 viticultural factors and 230 soil biological parameters. "The results show that soil microorganisms are threefold to fourfold higher under organic viticulture than under conventional viticulture in terms of biomass, respiration and activity. Tillage, the absence of soil cover and mineral fertilization are significantly deleterious to the whole soil biodiversity, whereas cover crops, organic fertilizers and addition of grapevine pruning wood are beneficial. Pesticides—especially herbicides—have an ecotoxicological impact on soil organisms, notably on nematodes with losses of up to two-thirds of individuals."

   "The pivotal role of biodiversity in soil functions implies that this degradation will have substantial consequences on the ecological and agronomical services provided by the soil for vine production. On this basis, we propose a potentially more agro-ecological and sustainable vine production system based on the more virtuous practices." Also noted, "Biochar inputs do not seem to have any recognized effect on biological parameters. Which would support the use of biochar for its beneficial properties without concern that there will be deleterious effects to the soil biology. And taking a further step in this logic, using biochar could have very definite advantages in vineyard moving to more organic management."

[9]Biochar in the vineyard: building a foundation for sustainability, S. Madden-Grey; https://anzbig.org/wp-content/uploads/2020/10/Simone-Madden-Grey-GW-Biochar-October-2020.pdf

[10]Kon-Tiki Kiln - Open Source Ecology

[11]Repurposing Grape Marc in Marlborough: The Way Forward From Assessment of Options to Next Steps; Jim Jones, Sarah McLaren, Qun Chen; 3 June, 2020; Massey University, NZ

[12]Role of Soil Organic Matter | NRCS Soils (usda.gov)

[13]Thanks to Jim Archuleta, Soil Scientist with the US Forest Service for this contribution.

[14]A meta-analysis of the ecotoxicological impact of viticultural practices on soil biodiversity; B. Karimi, J. Cahurel, L. Gontier, L. Charlier, M. Chovelon, H. Mahé, L. Ranjard; Environmental Chemistry Letters (2020) 18:1947–1966; https://doi.org/10.1007/s10311-020-01050-5 ; July 2020

8. Another look at the demands of viticulture with respect to soils and water—and specifically in advocacy for dry (i.e., non-irrigated) farming, the authors[15] note: "...biochar both regenerates soil by replenishing its organic matter and increases its ability to retain moisture, which is essential in dry farming." "And biochar, as stated earlier, is being explored as a remedy to soils that have been salinized by excessive irrigation and [to] enhance water retention."

9. Another meta-analysis[16], looked at biochar's effects on crop yields from research published between 1998 and 2017. The analysis concluded: "...that biochar addition to soil generally produced positive effects on crop yields." With the caveat: "Yield responses have been found to be relatively larger in low-pH and coarse textured soils, and with the application of nutrient- rich biochars (Biederman and Harpole, 2013; Jeffery et al., 2011; Liu et al., 2013), or in soils with small CEC and low levels of organic carbon (OC) content (Crane-Droesch et al., 2013)."

10. In a 4-year field study[17] in Tuscany, researchers found the addition of biochar improved production, crediting it largely to better water retention. From the report's abstract:

> "The effect of biochar application on vine yield and grape quality parameters is here investigated in a non-irrigated vineyard in Tuscany (central Italy). Results from four harvest-years showed a higher productivity, up to 66%, of treated plots with respect to their controls, while no significant differences were observed in grape quality parameters. The observed increase in productivity was inversely correlated with rainfall in the vegetative period, confirming the key role of biochar in regulating plant water availability. These findings support the feasibility of a biochar-based strategy as an effective adaptation measure to reduce the impact of water stress periods with no negative effects on grape quality."[17]

11. Research[18] looking at the use of biochar from pomace feedstock and it's ability to remove cymoxanil, a fungicide, found that a lower temperature char performed better than higher temperature chars. From the Abstract: "In this work, the adsorptive behaviors and mechanisms of grape pomace-derived biochar (GP-BC) were assessed for the removal of the pesticide [sic] cymoxanil (CM). The biochars were produced via pyrolysis carbonization at different temperatures (350, 550, and 750 °C) and batch adsorption experiments were conducted to determine various parameters. Our findings imply that GP-BC is a promising adsorbent for pesticide treatment and such an application creates an excellent closed-loop system.

[15]Climate Change and Water Management: Non-viability of Freshwater Irrigation in Viticulture; L. Johnson-Bell; The Wine and Climate Change Institute, Oxford, UK; Springer Nature Switzerland, 2019

[16]Biochar effects on crop yields with and without fertilizer: A meta- analysis of field studies using separate controls; L. Ye, M. Camps-Arbestain, Q. Shen, J. Lehmann, B. Singh, M. Sabir; Soil Use Management, 2020;36:2–18; DOI: 10.1111/sum.12546

[17]Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany; L. Genesio, F. Miglietta, S. Baronti, F. Vaccari; Agriculture, Ecosystems and Environment 201 (2015) 20–25; http://dx.doi.org/10.1016/j.agee.2014.11.021

[18]Assessment of adsorptive behaviors and properties of grape pomace-derived biochar as adsorbent for removal of cymoxanil pesticide; J. Yoon, J. Kim, H. Song, K. Oh, J.Jo, Y. Yang, S. Lee, G. Kang, H. Kim, Y. Choi; Environmental Technology & Innovation Volume 21, February 2021, https://doi.org/10.1016/j.eti.2020.101242

12. One of the most relevant field trials[19] for viticulturalists in California was by Doug Beck of the Monterey Pacific Vineyard Management Company. The findings from this study have been cited numerous times here and the reader is encouraged to download and read the report, as well as watch the video which describes the establishment of the 4 acre field trial as presented at the 2020 Biochar Forum: https://youtu.be/2mwRGuq_ty4. The report noted here is a follow-up presenting the data from the first two harvests. The data and economic analysis are compelling, and demonstrate, with the proper design and specifications, biochar can be a sound investment.

13. A cautionary study[20] of using biochar in soils summarizes 259 studies from 15 years of research. The review summarizes the possible adverse effects with these highlights:

- Adverse effects may arise due to changes in soil properties upon biochar addition.
- Soil organisms, mostly earthworms, suffer from biological adverse effects of biochar.
- Several unfavorable soil-biochar combinations were identified.
- A holistic approach is needed to reveal all possible, long-term adverse effects.

The paper concludes with tables linking the adverse effects on soil microorganisms, invertebrates, and general potential negative effects of biochar in soils, all linked to the original research.

[19]Current and Previous Field Research conducted by Monterey Pacific Vineyard Management, Pacific Biochar, UC Riverside, and Sonoma Ecology Center; https://napagreen.org/wp-content/uploads/2021/01/Monterey-Pacific-Vineyard-Management_Biochar-Trial.pdf

[20]A critical review of the possible adverse effects of biochar in the soil environment; M. Brtnicky, R. Datta, J. Holatko, L. Bielska, Z. Gusiatin, J. Kucerik, T. Hammerschmiedt, S. Danish, M. Radziemska, L. Mravcova, S. Fahad, A. Kintl, M. Sudoma, N. Ahmed, V. Pecina; Science of the Total Environment 796 (2021) 148756; https://doi.org/10.1016/j.scitotenv.2021.148756

Section 2.

For Grape Growers: Using Biochar in Viticulture

Section 2. For Grape Growers: Using Biochar in Viticulture

Biochar can address these grape grower's needs:

- Increase water retention
- Increase soil carbon
- Nutrient release leveling
- Soil structure management
- Soil biota improvement
- Soil contamination mitigation
- Pruning and marc disposal (by serving as a feedstock for biochar production)

Potential Uses of biochar:

- Nursery or rootstock growing media admixture
- Bulk soil additive at establishment
- Carrier for microorganisms, bioherbicides and biopesticides for root application or foliar spray for aphids or other removal prior to fruit harvest
- Foliar application of micronized biochar applied in solution as a carrier for the above treatments or alone
- Sanitary method of disposing of prunings (as feedstock for biochar) without open burning or landfilling, however quality control is important to ensure complete pyrolysis is achieved.

Benefits of biochar use include reduced disease[21], improved fruit, improved water retention/reduced irrigation costs, increased soil carbon, and long-term carbon sequestration. Specific research supporting these benefits can be found in Section 1, and anecdotal support from viticulturalists can be found in Section 3.

Biochar Application

- Bulk biochar at establishment: Bulk biochar will arrive in a walking floor trailer or super sacks typically. The char is best mixed with compost prior to application, at a rate of 10 to 25%. This will require some method of mixing bulk ingredients and then transportation to the field. A dump truck or trailer in concert with a track hoe or compact loader for trench or hole application; a manure or side feed-spreader to apply a broadcast layer or in-row application and a roto-hoe or tiller to blend with soil. Note: ideally, bulk biochar will be premixed with compost or a compost made with biochar as one of the initial ingredients.[22]
- Top-dressing or in-row mulch admixture: Similar equipment, preparations, and cautions to the establishment above, however the delivery as a mulch is most effective with a side delivery bulk unit like the silage wagon in Figure 1. For between-row broadcasting, a manure spreader would work well. If interplanting cover crops, the seed can be premixed with the biochar/compost mix being broadcast.
- Micronized biochar: Apply in solution with water or compost tea via an electrostatic or fogging sprayer. Alternately, for root applications a subsoil injection nozzle would be used. Arborists use this technique currently. A cautionary note about his application method is offered because of the potential for erosion of nozzles and pumps due to the hardness of the biochar particles.

Costs and Resources– The most current and applicable exploration of costs was published by the Sonoma Ecology Center[23] at a cost of $2000/acre at establishment, where the return on investment was fulfilled after the first growing season. States' Extension specialists have publications with reference costs of establishment, operating costs, and revenue scenarios which can be used for determining local/regional cost benefit analyses. While none of them currently include biochar in the establishment cost, it can be "plugged in" to the calculations as an initial investment. A list of biochar producers is available at the US Biochar Initiative's website to aid in finding suppliers: Directory by State | US Biochar Initiative (biochar-us.org/directory)

Here are Extension resources available from the top wine producing states:

- CA: Current Studies with Grapes/Wine - UC Davis Cost Studies
- MI: Growing Wine Grapes in Michigan – Grapes (extension.org)
- MO: Viticulture / Grape and Wine Institute / University of Missouri
- NC: The North Carolina Winegrape Grower's Guide | NC State Extension Publications (ncsu.edu)
- NY: Starting a Winery in Northern New York: Winery Establishment Considerations and Costs (cornell.edu)
- OR: Wine Industry Economics | College of Agricultural Sciences | Oregon State University
- PA: Starting a Winery - Grape and Wine Production - Food Safety and Quality (psu.edu)
- TX: Texas Viticulture & Enology - Advancing the science of grapes and wine (tamu.edu); Extension Publication: Texas hill budget[24]
- VA: Wine Grapes | Virginia Cooperative Extension | Virginia Tech (vt.edu)
- WA: Economic Tools: Grape and Wine Production | WSU Viticulture and Enology | Washington State University

The developing carbon credit market will have a significant effect on the economics of biochar use.

There are clear advantages for grape growers to market their "greening" efforts from using biochar, but it also offers the opportunity to profit from the long-term sequestration of carbon. Carbon markets are becoming more established as a climate change mitigation strategy and biochar is an established product with evaluation criteria in place. Current brokers in the US are Verra[25] and Puro[26] with other systems coming on line, making research into this financial avenue advisable.

[21] Section 1, Articles 7 and 11

[22] Section 1, Article 2

[23] Section 1, Article 12

[24] Texas Vineyard Budgets; D. K. Pate, E. Hellman, J. Johnson; Texas Hill Country Region; College of Agricultural Sciences & Natural Resources Technical Report T-1-602, Texas Tech University; 2008

[25] https://verra.org/voluntary-carbon-markets/

[26] https://puro.earth/

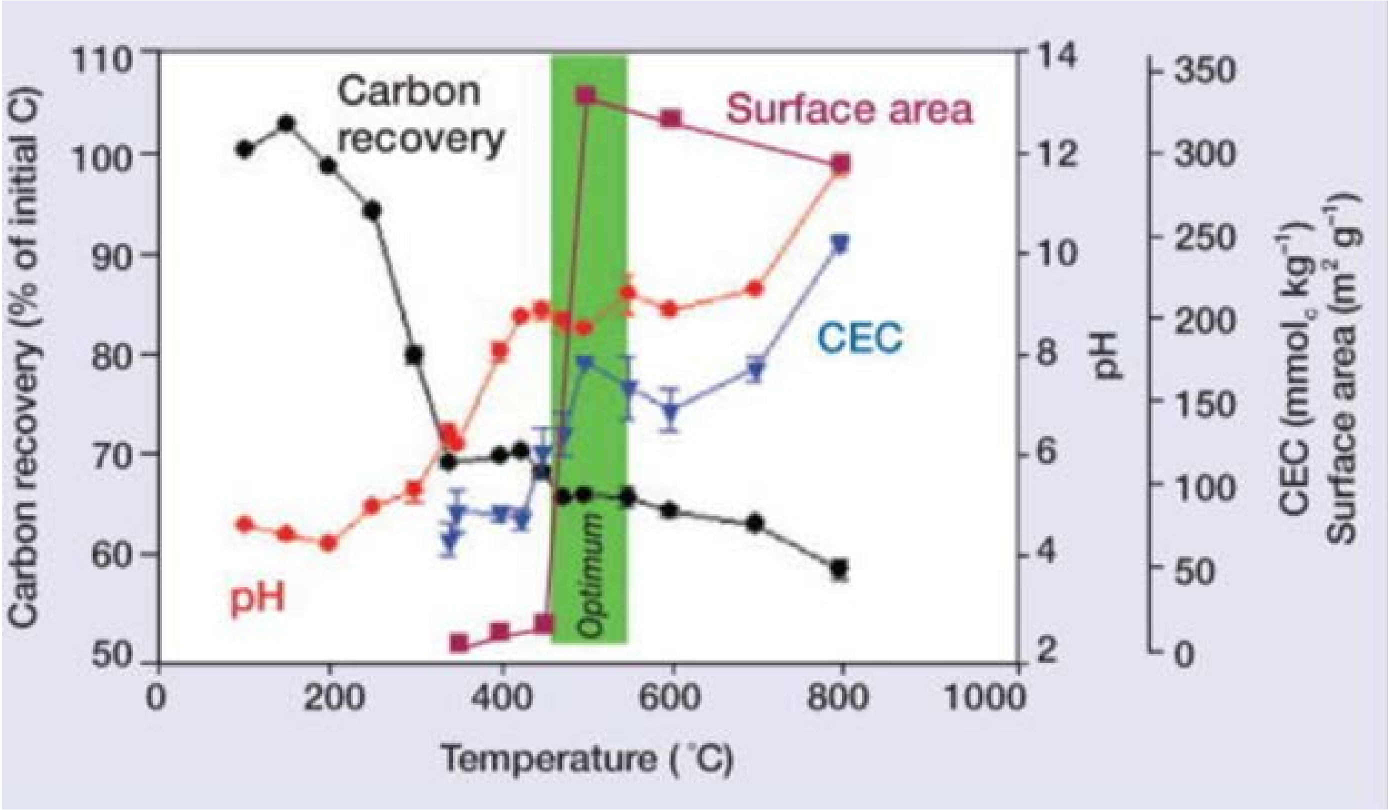
Understanding Biochar

It cannot be stressed enough that not all biochars are the same. It is important to understand what kind of biochar is needed to address specific growing constraints. Figure 2 illustrates generally what to look for in a biochar. Depending on the soil to which the biochar will be applied, and what constraints a grower wants to address (i.e., water holding capacity, soil compaction, soil organic matter [SOM]), a biochar can be considered. The grower or consultant can specify the biochar or, at the very least, commercially available biochars can be evaluated by looking at the lab test results. A good reference for biochar testing standards and biochar properties is available at the International Biochar Initiative website [27]. You can also see a quality certificate[28] for the char used in the Oasis Vineyard field trial discussed below and in Section 3.

Using Figure 2 to understand biochar properties better, a biochar made above 450°C will provide desirable characteristics—not too much liming effect, good CEC (cation exchange capacity), decent surface area expansion, and acceptable carbon recovery. To be certain of the characteristics, a lab analysis is essential—either provided by the producer or, ideally, from an independent lab. The carbon recovery line needs more explanation. The pyrolyzed carbon comes in two forms: stable (also referred to as recalcitrant) and labile (or reactive.) The stable carbon fraction will remain in the soil for a long time (decades to millennia.) The labile fraction will react with other elements in the soil and ultimately convert to CO2 within a few years. The higher temperature chars (with the most surface area) tend to have higher proportions of stable carbon. This is an important consideration for soil management planning, but also if carbon credits are being sought. These markets are becoming more established as a climate change mitigation strategy and should be included in any economic evaluation. Current brokers in the US are Verra[29] and Puro[30], but other systems are coming on line and researching this financial avenue is advisable.

The graph for Figure 2 is for a specific hardwood, but for comparison, the graph of other hardwoods will be very similar, a biochar derived from softwood will look slightly different, but grass or manure-based biochars will be very different[31]. More details about the considerations for specifying an appropriate biochar for a vineyard will be presented in Section 3. Getting input from a soil expert is advisable; Extension Agents from your local Land Grant University are a first-stop for a referral to those resources if you don't already have a consultant.

Figure 2: Change in Biochar Characteristics with Temperature



Lehmann, J. (2007), Bio-energy in the black. Frontiers in Ecology and the Environment, 5: 381-387. https://doi.org/10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2

[27] https://biochar-international.org/resources/

[28] https://pacificbiochar.com/products/blacklite-pure/&sa=D&source=editors&ust=1630246931033000&usg=AOvVaw3UIqs59d-I0GiC6M4qD2hK

[29] https://verra.org/voluntary-carbon-markets/

[30] https://puro.earth/

[31] Analyses of biochar properties; Allaire SE, Lange SF, Auclair IK, Quinche M, Greffard L; (2015); CRMR-2015-SA-5. Centre de Recherche sur les Matériaux Renouvelables, Université Laval, Québec, Canada

Section 3.

Growers’ Experiences with Biochar in the Vineyard

Section 3.
Growers' Experiences with Biochar In-theVineyard

This section explores recent field trials and experiences of wine grape growers who are using biochar. The most common benefit cited is its water retention capacity[32], resulting in increased yields without any negative impact on grape quality or wine taste.

The most rigorous field trial is the Oasis vineyard experiment begun in 2016 and still ongoing. This vineyard, managed by Monterey Pacific, Inc., is located outside of King City, CA in the Salinas Valley. It has been highlighted in the earlier Science section of this report (Article 12) and has been chronicled in numerous Wine industry publications (summarized below.) Results from this field research trial indicate that biochar and compost treatments can improve water use efficiency, vine growth, and harvest yields for newly planted vineyards in sand soils opposed to compost alone.

From the Pacific Biochar[33] website—one of the projects' two biochar suppliers:

- "The Oasis Vineyard Trial was initiated in 2016 to study how biochar and compost treatments impact soil water potential, vine growth, and harvest yields in a newly planted vineyard."
- "Significant increases in harvest yield were observed for all treatments with the highest yield in the biochar treatment, resulting in a 45% increase over the control. Increased pruning weight was observed for both the compost and the compost + biochar treatments; and higher cluster counts were observed for both the biochar and the compost + biochar treatments. Though the treatments resulted in increased plant vigor and crop yield, all treatments received the same irrigation regime throughout the trial, demonstrating improved water use efficiency where soil had been amended. Results from this field research trial indicate that biochar and compost treatments can improve water use efficiency, vine growth, and harvest yields for newly planted vineyards in sandy soils"

In an April 2016 Issue of Wine Business Monthly and article titled Vineyards Experiment with Biochar as Soil Amendment[34] by Ted Rieger, provided some background and interviewed Doug Beck about the project.

"Vineyard biomass from vine removal and pruned wood can be converted to biochar through more efficient and less polluting conservation ag burning practices, as some vineyard operations have implemented, rather than standard vine pile burning that simply produces smoke and ash. Agricultural and biomass waste disposal, in general, is an issue of greater concern in California. A number of biomass (waste to energy) power generation facilities have ceased operation recently as a result of expired contracts with utility companies that are no longer paying favorable rates for biomass-produced energy. The potential use of pyrolysis equipment to process biomass into biochar offers a preferable alternative to burning or disposal in landfills."

- "Doug Beck is a soil scientist and agronomist with Monterey Pacific Vineyard Management Company in Monterey County who manages about 12,000 acres of vineyards that include production-level vineyards with yields of 5 to 10 tons per acre and high-end vineyards."

[32]Looking back at Figure 1, in the introduction, you can imagine all the pockets and crevices in the char filled with water from the soil. Due to the small compartments, the release is slow--which adds days to the typical drying cycle time. The same holds true for nutrients entrained in the water.
[33]https://pacificbiochar.com/
[34]https://www.winebusiness.com/wbm/?go=getArticleSignIn&dataId=166324

- "Beck admitted, "One of the drawbacks of biochar is that it's really expensive," noting that applications have run about $7,000 per acre for the biochar alone at the rate of 10 tons per acre. But he noted, 'If the lifespan of the product and its benefits are long-term, it can be worth it if one application provides benefits over 20 years of a vineyard's life. That's why we're doing trials: to be able to show the owners of the vineyards we manage whether or not it's worth the cost. We are at the early stages of biochar use and are very interested in its potential. We are trying to get a handle on the varying quality of biochar and we're trying to follow the current science.'"

To close the loop on the current status of this experiment-in-progress[35], the data gathered by Monterey Pacific Vineyard Management Company and Pacific Biochar Benefit Corporation showed the return on investment for adding the biochar was paid off with increased yields in the first harvest, with higher profit expected for the life of the vines.

Another group of vineyards in Oregon have used biochar generated by pyrolyzing the debris from the land clearing and preparation effort at Big Table Farm near Carlton, OR. There is a video at the Vineyard's website[36] which shows the air curtain burner technology used to generate the biochar.

The owner, Clare Carver, shared that in 2020 they used a biochar-compost blend at a rate of two shovelfuls per plant at the base of each plant. The vineyard, in the Willamette Valley, is neither tilled or irrigated and she noted they made it through the triple digit heat wave in June 2021 with only minor losses.

Carver kept about 40 tons of the biochar on their farm, using 3-4 tons added to deep bedding in their livestock barn with the rest mixed with their compost. They tried both a 25% and a 15% biochar/compost mix and left it 3 to 4 months to inoculate. Their compost is a mix of bedding from overwintering cows and grape pomace. The first year they spread compost with and without biochar on their lower pasture and noted the regrowth was stronger where the char was mixed in with compost.

Another farmer bought some of Big Table's biochar to use and had similar success. Koosah Farm, near Amity, OR37, purchased about 40 tons of the biochar produced on Big Table's farm in 2019. It was applied to about 16 acres in three different ways. The bulk of it was broadcast on 10 acres with a manure spreader after being inoculated with

[35]https://napagreen.org/wp-content/uploads/2021/01/Monterey-Pacific-Vineyard-Management_Biochar-Trial.pdf
[36]https://www.bigtablefarm.com/

compost tea. The second portion was composted with cow manure, straw and green manure. The resulting compost was used to enhance hugel beds and other permaculture plantings. The third portion was top dressed on 4 acres of established vineyard in hopes of eventually improving water holding capacity.

When asked about results, Kevin Chambers said, “Anecdotally, we’ve observed what must be improved water holding capacity in all three applications. As further comparison, the 10 acres where we applied over 2 tons/acre and impregnated with compost tea, was severely rocky soil with only 1-2” of water-holding capacity. Those acres were planted with grapevines in March of 2020, and dry farmed since. Those vines have developed so well, we’ll be cropping them next year. As a comparison, we developed about 28 unirrigated acres on similar soils in 2016. Those vines were not cropped for four years. So, with charged biochar we gained a full year of development.”

The last recipient of Big Table’s biochar is Mimi Casteel of Hope Well Winery near Salem, OR[38]. She had this to say about her experience: “I integrated it [5 supersacks worth of char—about 6.5 cubic yards] into my existing compost pile, which was about a 40 ton pile, manure based, with LOTS of green/carbon inputs from the farm. We tumbled the char with food waste collected from local groceries (fruit and veg only) and fed it to our pigs on top of the compost pile. They ate and processed both the biochar and the food, and their manures were then turned into the compost pile and aged for more than a year. I applied it to my weakest blocks in winter of 2020/early 2021, and while I do not have controls in those blocks I can say without hesitation that [our weather has been] hotter and drier, earlier, this year, and I can’t believe how well those blocks are doing. I have been no till, dry farmed from the beginning, and my interest is around restoring the carbon that would have historically been lain down by periodic fires. We’ve grown our organic matter over time, but I’m very keen to see what changes we see when we repeat our soil tests next year.”

Further anecdotal experience is found in the article “Biochar: The Vineyard’s Next Big Thing”[39] by the Wine-Searcher staff, posted on May 25,2020.

- “Jake Neustadt, the vineyard manager for Bedrock Wine Company in Sonoma, California, explains: ‘We take over a lot of old vine sites that have been mistreated for decades, in terms of over cultivation and stripping of organic matter. The farmers may have been disking four times per year, and on sloping vineyards, all the topsoil has slid to the bottom of the hill. In those sites you have very little organic matter.’ Bedrock started using biochar about seven years ago when rehabilitating abused vineyards. ‘The biggest thing for us in rehabilitating a vineyard, before we see a change in the vines themselves, is establishing a healthy cover crop. With biochar, suddenly the soil retains everything better (nutrients, microbes, water), so we see a big increase in cover crop biomass pretty immediately. This is the jolt that makes everything happen.”
- “For his experimental Popelouchum vineyard in San Juan Bautista, Grahm applied biochar prior to planting. The vineyard is located on the edge of where dry farming is possible in California, and one of his hopes in using biochar is that it will allow him to dry farm. From a terroir perspective, this seems like a great deal. If all changes to a site deform terroir, Grahm is trading the application of a benign terroir deformer (and potential terroir enhancer) to gain full access to a very important aspect of terroir: enabling the vintage to be guided entirely by rainfall, as opposed to human irrigation choices”
- “Grahm points out that, in California, ‘we don’t have soils that are rich in available minerals; they’re very eroded. Especially in sandy soils, biochar is great in enhancing the uptake of minerals. If you look at Switzerland, there’s a lot of rock that is currently being eroded and released into the soil solution, biochar doesn’t have such a significant impact there. In California, with both mineral deficiency and drought, it’s particularly beneficial for our conditions.’”

End Note: From these shared experiences you can see there have been significant successes using biochar in vineyards. The benefit of biochar’s water retention is probably the clearest benefit, but the nutrient leveling effects and increased soil carbon (SOM) are also demonstrated in the grower’s increased productivity. While the soil types were not identified by most growers, it must be emphasized it’s an important factor when considering biochar enhancement, whether incorporated in the soil or as compost/mulch. While there are few instances of negative effects from biochar being used in vineyards, the research presented in section 1’s article 13 demonstrate it’s possible.

[37] https://koosahfarm.com/

[38] https://www.hopewellwine.com/

[39] https://www.wine-searcher.com/m/2020/05/biochar-the-vineyards-next-big-thing

Section 4.

For Biochar Producers: Market Potential for Biochar in the Grape Industry

Section 4. For Biochar Producers:
Market Potential for Biochar in the Grape Industry

Biochar has potential application in the viticulture industry as a soil amendment. Its ability to retain soil moisture is especially relevant given the many regions grapes are grown, however, it can also increase soil carbon, level nutrient release, improve soil structure, and stimulate soil biota. Biochar can be used in the growing medium for nursery or rootstock, applied at the time of vine planting, or used as an enhancement to compost or mulch throughout the growing season via surface application. Biochar also has the potential to serve as a carrier for other amendments used in the industry, and vine prunings or waste can be used as a feedstock to produce biochar. Depending on the application, biochar can be used at different volumes, but will likely be handled in bulk truckloads or supersacks.

The US Viticulture Market and Its Distribution

The US had 920,000 acres in grape production in 2020, down 10.2% since 2015[40]. Table 1 shows the production distribution of grape operations in the US and Table 2, by State, for 2017, the most recent year complete data are available. Table 1's 2017 percentages illustrate the different grape market splits.

Table 1: US Grape Production and Processing Distribution

US Grape Statistics				
	2020	% of total	2017	% of total
GRAPES - ACRES BEARING	920,000		997,800	
GRAPES - PRODUCTION, IN TONS	5,940,000		7,383,850	
FRESH MARKET GRAPES, PRODUCTION IN TONS	960,100	16.16%	1,030,310	13.95%
PROCESSED GRAPES, MEASURED IN TONS	4,979,900	83.84%	6,352,850	86.04%
DRIED GRAPES, TONS			1,198,000	16.22%
JUICE GRAPES, TONS			451,900	6.12%
WINE GRAPES, TONS			4,662,950	63.15%

[40]USDA National Agricultural Statistical Service

Table 2: Total 2017 Grape Acreage by State

State	Acreage	% of US Total	State	Acreage	% of US Total
CALIFORNIA	776,700	77.8%	OHIO	1,726	0.2%
WASHINGTON	77,629	7.8%	MISSOURI	1,528	0.2%
NEW YORK	33,142	3.3%	ARIZONA	1,538	0.2%
OREGON	23,871	2.4%	WISCONSIN	911	0.1%
PENNSYLVANIA	13,615	1.4%	TENNESSEE	903	0.1%
MICHIGAN	13,126	1.3%	IOWA	886	0.1%
TEXAS	4,888	0.5%	COLORADO	844	0.1%
NORTH CAROLINA	2,974	0.3%	ALABAMA	570	0.1%

Table 2 shows the West Coast predominance in viticulture, however the full NASS data shows there are opportunities to supply biochar to vineyards in every state but Alaska. Wine grapes are typically a higher percentage of the grape crop in most states as compared to CA—where most of the domestic raisin and table grapes are grown.

Table 3 presents the most recent statistics available for the wine industry which, when compared with the older acreage data may offer some perspective on the regions of growth and opportunity.

Table 3: US Wine Production

U.S. Wineries - By State
January 2020
Source: Wines Vines Analytics

State	Winery Count	%
California	4,613	44%
Washington	812	8%
Oregon	809	8%
New York	411	4%
Texas	406	4%
Pennsylvania	308	3%
Virginia	307	3%
Ohio	280	3%
Michigan	211	2%
North Carolina	175	2%
Missouri	154	1%
Colorado	150	1%
All other states	1,836	18%
Total U.S. Wineries	10,472	100%

U.S. Wineries - Annual Production (Cases)
2019 Production
Source: Wines Vines Analytics

State	Winery Count		%
California	4,613	287,000,000	86%
Washington	812	15,400,000	5%
New York	809	12,000,000	4%
Oregon	411	4,600,000	1%
Texas	406	1,800,000	1%
Michigan	308	1,300,000	0%
Illinois	307	1,000,000	0%
North Carolina	280	1,000,000	0%
Pennsylvania	154	950,000	0%
Virginia	150	950,000	0%
Ohio	1,836	900,000	0%
All other states	10,472	5,000,000	2%
Total U.S. Wineries		331,900,000	100%

Note: Winery production includes all wine produced at a location including custom production for other wineries. When summary totals are reported geographically, these custom amounts are netted out to prevent double counting.

Using the historic 30-year rotation of productive grape vines, there should be an average of 33,000 acres replanted per year across the US. For biochar producers, a 1% market penetration would be supplying biochar for 330 acres/year, and using a 10 tons per acre (T/A bone dry weight[41]) application rate for new planting[42] , that's 3,300T/year needed[43] . The char and compost (or other fill mix) would be placed in a trench or in individual holes prior to the vines, then backfilled with soil.

Giltrap Side Feed Silage Wagon

The combined need for biochar based on a **1% market penetration** is roughly **10,000TPY.**

At a bulk price of **$200/CY,** this equates to **$18.5M** in revenues at **9.25 CY/T.**

There is a cohort of grape growers who apply a top dressing and mulch[44] covering along the rows of vines annually. This is done using a side delivery bulk feeder (similar to a silage feed wagon, shown at left.) Using a typical mix of 50% compost, 10% biochar, and 40% mulch , with a market penetration of 1% there's an annual need for biochar of 14,900 tons/yr.[45]

Market Highlights:

- Biochar customers in the viticulture industry include wine, table, juice, and dried grape growers, vineyard management services, compost operations, and soil blenders.
- Biochar producers need to be aware that vineyard management companies (VMC) are responsible for more than 75 percent of the farms in the Napa Valley[46] alone.
- Compost is also becoming a more prominent amendment—and should become more available as CA legislation mandates more organic waste to be composted as opposed to landfilled. Given the "supercharging" of compost with biochar, there is significant market potential with both compost operations and with VMC's who're specifying the horticultural management of hundreds of thousands of acres in CA.

[41]Moisture Content Effect: If the bulk density of biochar is 8lbs/ ft3 and water is 62.4lbs/ ft3, there will be 108lbs of water in a 50% moisture content mix. The water component would take up only 1.7 ft3 or 6.3% of the volume. For consistency, biochar-by-volume has been used unless noted.

[42]Application rate derived from field trials and research projects cited and explored in this document.

[43]Calculation details: Biochar is typically 7-9lbs/CF dry; using the 8lbs median yields 216lbs per CY. At 216lbs/BDCY (bone dry cubic yard,) and assuming a 50% moisture content, would require 10.6T/A or 106CY/A with a total need of 349,800 CY.

[44]Section 3, Articles 2, 4, and 10

[45]Mulch Calculation details: 4" deep, 18" wide= 0.5 CF/lineal ft or 54 lineal feet per CY. With the mulch cross section having sloping sides, assume 25% less volume per foot, which increases lineal footage to 68. Using a 6ft vine spacing on average with 8' row spacing, there are 908 vines per acre or 5500 LFT per acre. At 1% market penetration and 10% biochar inclusion that would be 9200A mulched X 5500LFT of row per acre÷68 lineal ft per CY= 745,000CY X 0.10= 74,500 CY at 200lbs/CY dry= 7,450T/yr.

[46]2020 Sample Costs to Establish a Vineyard and Produce Winegrapes; S. Kurtural, D. Stewart; UC Davis Cooperative Extension, Department of Agriculutural and Resource Economics

Costs Analysis– Biochar for use in Viticulture will have similar characteristics to that used in other ag applications[47] unless there's a specific need or specification by the buyer to complement a particular soil or cultural accommodation. There is potential for suppliers with mobile equipment to enter into a symbiotic relationship where the biochar is made from the prunings and marc (pomace) on-site or locally and use it directly or in collaboration with a compost operation. Research has shown this [grape residue] biochar to be particularly beneficial[48], increasing water retention by 23% as it provides the additional benefit to the growers from both phytosanitation and disposal aspects.

Grape growers have a long-lived crop with relatively high profit margins (compared to other commodity crops) which allow them to consider investing in biochar supplementation as long as the case is made effectively for that investment and what returns it can provide. The work done by Doug Beck in the Californian Oasis Vineyard[49] provides the most current and dependable data. In 2016 they paid $200 per ton ($2000/planted Acre) for biochar which was mixed with compost and placed in a trench in which the vines were planted. Subsequent evaluation found the yields in their first two crops were improved over the control plots (with compost, but no biochar), yielding a return on investment of less than 1 year (once harvests began in year 3.) No data are available for surface applied biochar in a mulching/nutrient mix.

The 2020 cost of planting an acre of grapes in Napa Valley[50] were determined to be $13,995 per acre without soil supplements. A $2000 per acre biochar cost would add 14% to the planting costs, but when all costs are considered, the total per acre cost is $37,096, of which biochar would add 5%.

There is further research and anecdotal evidence of crop improvement in dry (i.e., non-irrigated) viticulture applications, detailed in Section 3[51] as well as by most of the vintners' experience in Section 4.

Biochar's Competition comes primarily from the need for and cost of:

- Synthetic and organic fertilizers
  - "The three most common amendments are gypsum, compost, and lime. Gypsum is probably the most widely used soil amendment in California vineyards[52] ". In a presentation on Fertilizer vs. Compost Costs[53] calculated, for the same effect, synthetic fertilizer cost $ 46/ac and compost cost $240/ac. The author noted, "Bottom line, costs for each will vary, depending on the producer's farming goals and soil nutrient status."
  - Organic supplements are typically considered "wide spectrum, low intensity" because, while they're low in NPK, they supply micronutrients which stimulate soil biota, and releases the nutrients to the plants. The basic supplements of gypsum, lime, and compost are all considered to be organic supplements (whether they're certified as Organic or not).
- Chemical and organic sprays for herbaceous, insect, and fungal control
  - There are hundreds of grape approved synthetic pesticides, herbicides, and fungicides. Probably the largest numbers of vine diseases are caused by fungi, and the most common chemical tools for vine disease control are fungicides.[54] For organic production, integrated pest management is recommended: "If you choose not to use synthetic pesticides, then your goal should be to maintain the vineyard as clean as possible. Weeds serve as an excellent host for insect pests fungal pathogens and should be routinely

[47]Biochar Classification Tool Interface - biochar-international

[48]Section 3, Article 5

[49]Section 3, Article 12

[50]Sample Costs to Establish a Vineyard and Produce Winegrapes, Cabernet Sauvignon, North Coast Region, Napa County, Crush District 4, 2020 (ucdavis.edu), p. 16-18

[51]Section 3, Articles 3, 4, and 8

[52]Soil Amendments for Vineyards - What are the Benefits?, S. Baum; https://www.lodigrowers.com/soil-amendments-for-vineyards-what-are-the-benefits/

[53]Comparisons of Manure, Compost, and Commercial Fertilizers; Clain Jones, Montana State University Extension Soil Fertility Specialist; Comparisons of Manure, Compost, and Commercial Fertilizers

[54]Pest Mangement Guide for Wine Grapes in Oregon; Oregon State University Extension Publication EM 8413; P. Skinnis, J. Pscheidt, M. Moretti, V. Walton, Achala KC, C. Kaiser, Revised 2021

controlled by all grape growers. Vineyards differ from orchards in that the foliage and fruit in vineyards are typically much closer to the ground."[55]

  - All synthetic sprays require training and some require licensing. Personal protective equipment is a must. Labels list approved use on applicable crops.
  - Biochar has proven effective[56] as a mitigant of soil effects from the use of synthetic chemical applications, and in some cases with some herbicidal and fungicidal capacity itself.

- Vermiculite in nursery applications: Vermiculite is used in potting soil to increase water and nutrient retention and aerates the soil. In research sponsored by the US Forest Service[57] concluded "that biochar provides benefits equivalent to vermiculite in terms of key nutrient availability and total biomass productivity."
- Compost: Compost is one of the most popular supplemental materials used in the viticulture industry. Biochar is a proven and cost effective supplement to compost[58].

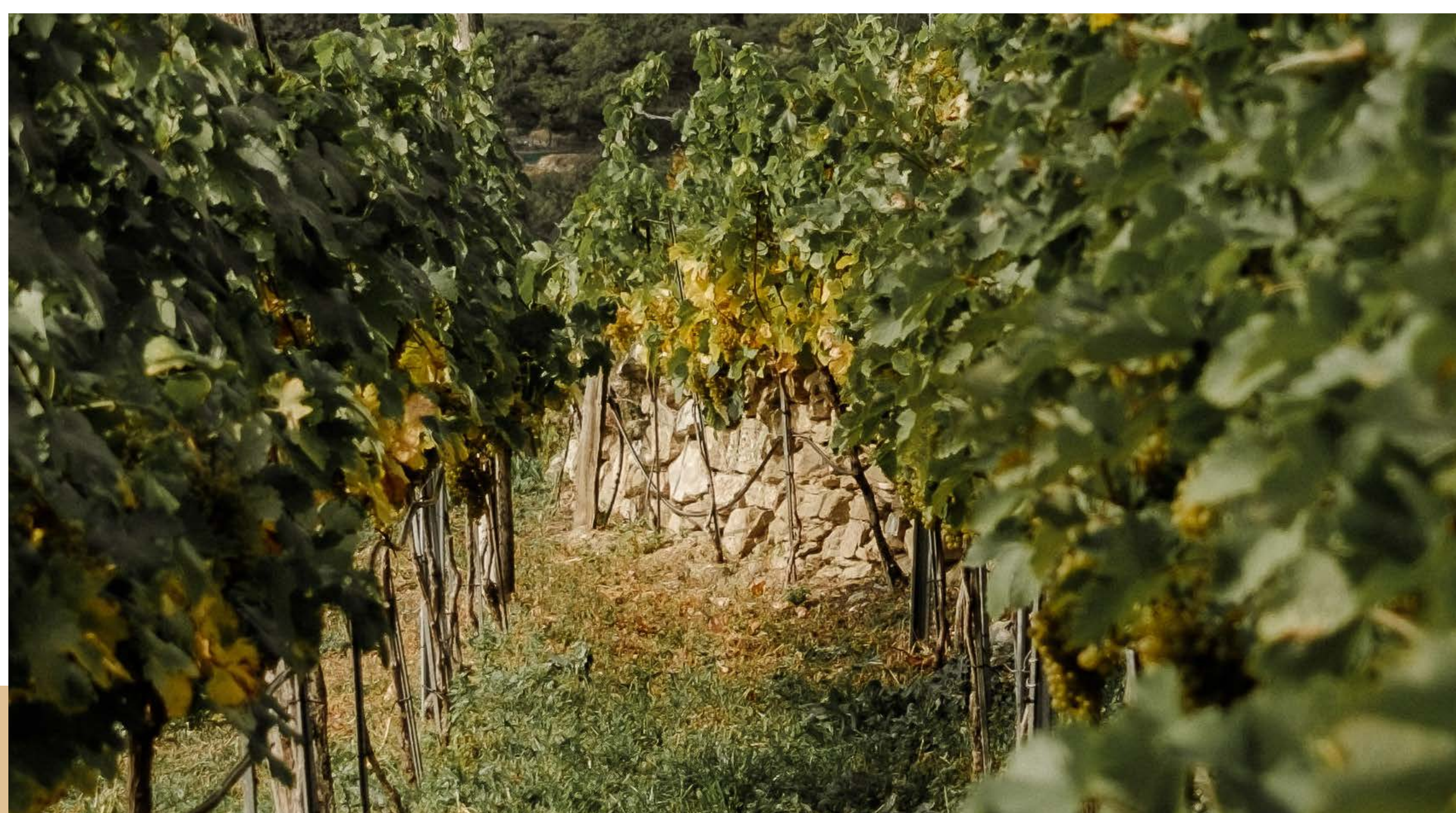
A point to be made with vineyard owners/managers is that biochar used in the establishment of a vineyard could be considered a one-time capital investment with its initial cost amortization balanced by increased yields. Again, the Oasis Vineyard study provides support for that argument and as a baseline for building the case to potential biochar customers.

[55] Weed Management in Organic Vineyards; University of California Statewide Integrated Pest Management Program; http://ipm.ucanr.edu/PMG/r302700511.html

[56] Section 1, Articles, 2, 7, 11

[57] Biochar as a Substitute for Vermiculite in Potting Mix for Hybrid Poplar; W. Headlee, C. Brewer, R. Hall; Bioenerg. Res. (2014) 7:120–131; DOI 10.1007/s12155-013-9355-y

[58] Section 1, Articles 2, 4, 6, 7, 12



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