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BRIEF REPORT

Banishing the myths and dogmas surrounding the biotech Stradivarius

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Societal Impact Statement

The impact of global warming on wood formation means that it is becoming increasingly difficult to find superior-quality resonance wood for the production of musical instruments. Using fungi, we can mimic the effects of a cold climate on wood, to produce biotech violins with a tone matching those of a Stradivarius. Our work has sparked worldwide interest from the media, music lovers, and violinmakers. Here we address concerns raised about the biotech violin and detail scientific advances made since the original publication of our work. We believe this mycowood technology will enable affordable and acoustically superior instruments to become available to talented young musicians who would otherwise be unable to afford their own Stradivarius.

KEYWORDS

acoustics, biotech violin, Blind test, Caspar Hauser II, mycowood, wood decay

1 | THE MOTHER OF ALL VIOLINS

Antique Italian violins like those crafted by Antonio Stradivari and Giuseppe Guarneri “del Gesu” during the 17th and 18th centuries can fetch millions of dollars in the open market, a price tag that makes these unique bow instruments off-limits for most young and aspiring violinists. A consensus among experts is that these instruments deliver superior sounds to violins made since the Baroque era, and there have been several hypotheses—both scientifically supported and unsupported ones—attempting to elucidate the cause of such a superior sound quality. Claims range from a mysterious ingredient to the wood, or a secret varnish recipe (Echard et al., 2010; Mancini, Tromba, & Zanini, 2006; Nagyvary, DiVerdi, Owen, & Tolley, 2006; Nia et al., 2015), to the instruments' unique shape and even good old-fashioned genius of the ancient master violinmakers. However, the most convincing evidence relates to the climate at that time, where the “little Ice Age” (Mauder Minimum, 1645–1715) caused European spruces (*Picea*

abies) that form the instruments' top plate to grow regularly, giving the instrument a fuller and more consistent sound (Burckle & Grissino-Mayer, 2003; Stoel & Borman, 2008). Making modern-day bow instruments superior may mean trying to recreate the effect of cold climate on wood, which we managed to achieve with the help of wood-decomposing fungi. In warmer climates, spruce trees produce more latewood, a denser and heavier wood that affects the vibrational properties of the instrument. Stradivari used alpine spruce from higher elevations in the Italian Alps, where owing to a colder climate the wood was far more homogenous. We used fungi that specialize in thinning latewood cells, thereby recreating the uniform structure of Stradivari resonance wood. Superior quality Norway spruce and sycamore maple (bottom plate) resonance wood is homogenous throughout early-and-latewood, which is referred to as the high radiation ratio (ratio between sound velocity and density) in sound engineering. The ideal wood cells for strong vibrational properties are characterized as small with thin cell walls (Spycher, Schwarze, & Steiger, 2008). For mycowood, we

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use tonewood from the Swiss Alps with a high ratio of speed of sound to density, as these properties increase the sound emission of the instrument, meaning that the plate amplitudes are high in relation to the force that excites the strings. The enhancement of resonance makes the difference between a violin of average quality and one that is suitable for a top soloist.

2 | MYCOWOOD FOR BIOTECH VIOLINS

It has been around a decade since the publication of our seminal work on the selection and application of two wood-decomposing fungi to the wood of European spruce and sycamore maple (*Acer pseudoplatanus*) for the top and bottom plates of a violin, respectively (Schwarze, Spycher, & Fink, 2008). *Physisporinus vitreus* (Figure 1) was used for the spruce top plate with *Xylaria longipes* (since replaced with *Schizophyllum commune*) being used for the bottom plate to improve the wood's acoustic properties. The replacement to *S. commune* was due to black zone line formation caused by *X. longipes*, an aesthetic artifact that devalues the classical appearance of a violin. The latter fungi engineered the acoustics of the wood through homogenous degradation of late-wood tracheids, giving the future violin the sound pattern of those produced in Cremona, Italy, during the little Ice Age. In addition, we selected fungi based on their ability to target certain wood properties while leaving other regions intact. For degradation of lignin, Laccase is produced and secreted in high amounts by *P. vitreus*. Laccase activity is significantly enhanced by the addition of veratryl alcohol and copper to the growth media. These factors were considered during upscaling of mycowood production. The aim was to achieve the desired effect without appreciable changes to mechanical properties that would otherwise render the mycowood undesirable for violinmaking. Microscopic assessment of the incubated wood and measurements of five physical properties (density, modulus of elasticity, speed of sound, radiation ratio, and the damping factor) using resonance frequency revealed that in the wood of both spruce and maple there was a reduction in density, accompanied by relatively little change in the speed of sound. Thus, radiation ratio had increased from "poor" to "good", on a par with "superior" resonance wood grown in a cold climate (Schwarze et al., 2008). The increase in the damping factor is an important side effect of the fungal treatment as this reduces the often-irritating high notes of a violin and makes the instrument sound warmer and mellower, typical for many antique Cremona violins. We refer to the wood with superior tonal properties produced by the fungal treatment as mycowood (Schubert & Schwarze, 2011). The term mycowood was originally coined "myco-holz" by Walter Luthardt, who invented a method for pencil production during the early 1960s in the former German Democratic Republic (Unbehaun, Dittler, Kuhne, & Wagenführ, 2000). However, once manufactured, the instrument is called the biotech violin (Anon, 2010). Our main objective was to develop a method to counteract shortages in supplies for high-quality tone wood.

3 | BLIND TESTS FOR EVALUATING THE SOUND OF VIOLINS

Since the beginning of the 19th century, violins from Stradivari have been compared to instruments made by other violinmakers in "so-called" blind tests, with the most acclaimed test organized by The British Broadcasting Corporation (BBC) in 1974. In the blind test, the world famous violinists Isaac Stern and Pinchas Zukerman together with the English violin dealer Charles Beare were challenged to identify the "Chaconne" Stradivarius made in 1725, a "Guarneri del Gesu" of 1739, a "Vuillaume" of 1846 and a modern instrument made by the English master violinmaker Roland Praill. The result was a surprise, as none of the experts could correctly identify more than two of the four instruments, with two of the jurors even affirming that the modern instrument was actually the "Chaconne" Stradivarius. On September 1, 2009, at the Osnabrücker Baumpflegetage in Germany, an audience of arborists and three acoustic experts took part in another blind test using five violins. One of the violins was a \$2 million Stradivarius owned by Nigel Brown (founder of the Stradivari Trust, <https://stradivaritrust.org/>), which was made in 1711. For consistency, the other four violins were made from a single tree of both Norway spruce and sycamore maple. We had commissioned the violinmaker Michael Rhonheimer of Baden, Switzerland, to build two untreated and two mycowood violins (Opus 56 and 58). The British violinist Matthew Trusler played the five instruments before the listeners were asked to identify the Stradivarius. While 113 participants chose a biotech violin, only 39 correctly identified the Stradivarius, with the two untreated violins only receiving 3 and 17 votes, respectively. According to this blind test, a large and significant majority favored a biotech violin.

4 | CRITICAL RECEPTION OF THE BLIND TEST IN GERMANY

In general, the new biotech violin was greeted with universal critical acclaim. The results of the blind test were subsequently commented upon in Nature Biotechnology (Anon, 2010). Time Magazine considered the biotech violin to be one of the 50 best innovations of 2009. Numerous articles on the project were published in magazines, such as Discovery Channel, National Geographic, The Strad, and the Economist. In addition, Leonardo Film aired a documentary in German and English from the project entitled "Stradivari's Heirs: How scientists uncover the secrets of the Stradivarius".

However, a number of issues have since been raised concerning the rigor of the scientific tests behind the biotech violin. A week after the blind test in Osnabrück, the violinmaker of the two mycowood violins, Michael Rhonheimer, wrote a letter to the German Association of Violinmakers highlighting concerns about the biotech violin that lacked substantive evidence. One of the concerns related to the mechanical properties of the biotech

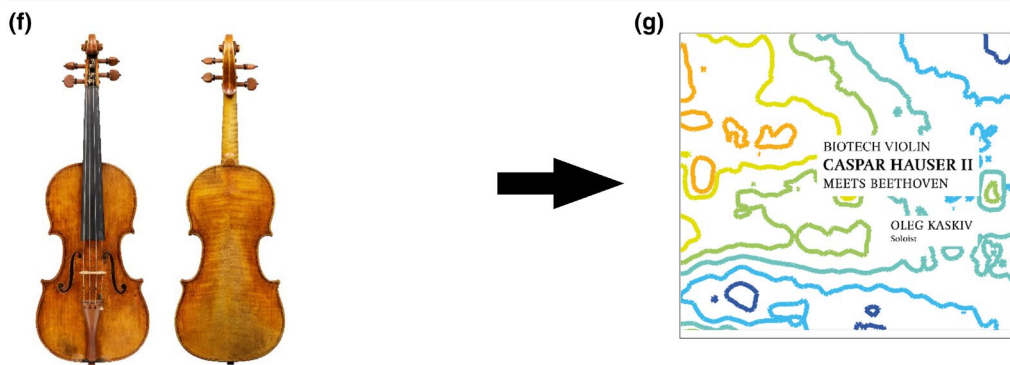
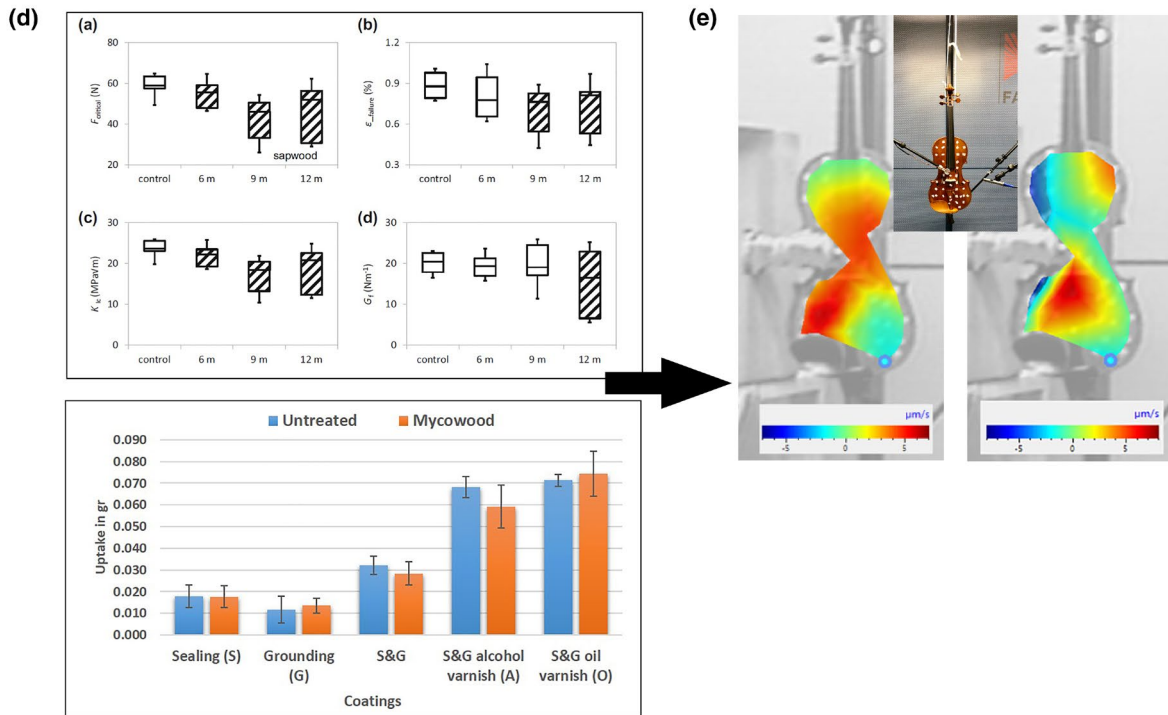
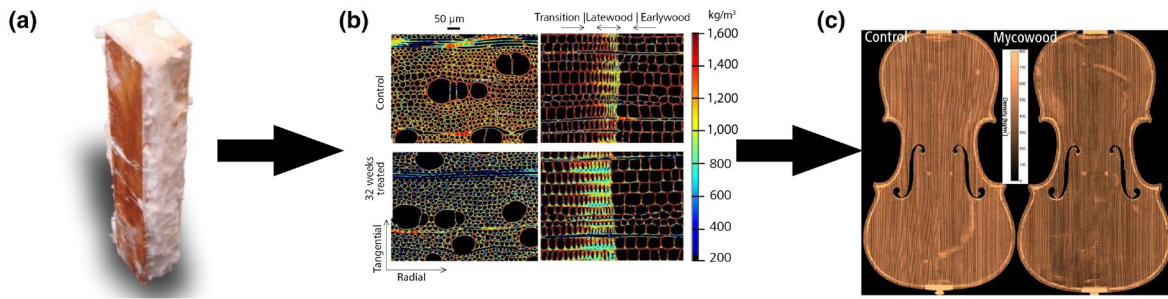


FIGURE 1 Technology transfer of mycowood from science to product which combines (i) science (fundamental discoveries and basic research) with (ii) technology development (process of performance assessment and optimization) and (iii) technology transfer (industrial application). (a) Colonization of wood by *P. vitreus* under controlled conditions; (b) transverse section of maple (left) and spruce wood (right) showing density distribution in tomograms. Untreated (top) and mycowood (bottom); (c) X-ray computed tomography (CT). Left: Untreated top plate. Right: Top plate made of mycowood showing more homogeneous density distribution in the region of the f-holes; (d) top: Left box-and-whisker plots of critical force, strain to failure, critical stress intensity factor, and specific fracture energy of controls and mycowood. Bottom: Varnish uptake by untreated wood and mycowood showing no significant differences; (e) top: acquisition setup for the vibration field of the front plate by a scanning laser Doppler vibrometer and the radiated sound by a microphone array. Two recorded vibration mode shapes at 540 Hz and 780 Hz; (f): top (left) and bottom plate (right) of the Casper Hauser II made from mycowood. Images from Jan Roehmann; and (g) cover of the first recording of Beethoven's Violin Concerto second movement by Oleg Kaskiv on the Casper Hauser II with the Gstaad Festival Orchester. Cover design by Empa

violin with Rhonheimer stating that the wood-decomposing fungi used in our experiments to alter the acoustics would remain alive and active and, in time, fracture the wood of the instrument. The argument lacks validity, however, as once an optimum wood density is reached in the top and bottom plate, the wood is sterilized with ethylene oxide, a gas that kills both bacteria and fungi. Furthermore, we assessed the failure load and the critical stress intensity factor in wood after prolonged incubation periods (6, 9, and 12 months). Fractures were found to occur in mycowood after incubation periods of 9–12 months, but not after 6 months (Sedighi Gilani, Heeb, Huch, Fink, & Schwarze, 2017; Sedighi Gilani et al., 2016). In fact, Simon Wiener, a student of Zakhar Bron of the Royal Academy of Music in London, played a biotech violin for 2 years (from 2014 to 2016) from mycowood incubated for only 6 months. While playing the instrument, Wiener confirmed that the violin had been in very good condition.

A second point raised by Rhonheimer concerned the rapid absorption of varnish by mycowood, thus significantly altering the acoustics. However, we have shown that there are no significant differences in varnish uptake by mycowood compared to untreated wood (Lämmlein, 2020; Figure 1d). Fungi do not alter the anatomical wood structure over the incubation period that might affect varnish uptake to any significant degree. Another argument suggests that fungal treatment of the tone wood would represent a health risk, exposing the violinist to spores and mycotoxins when playing the instrument. Concerning the latter, it is important to assert here that both fungi used for the top and bottom plates are non-sporulating and are registered as class one organisms, that is, are not harmful to humans. Finally, Rhonheimer contended that 95% of a violin's sound quality was the result of the artisanship of the violinmaker with the remaining 5% being the result of the wood quality. Our blind test in Osnabrück suggested otherwise, though.

5 | PAST AND CURRENT RESEARCH ON MYCOWOOD

Over the past decade, we have conducted a number of studies on the nature of the fungi used in violin making and their impact on the mechanical properties of mycowood (Table 1; Figure 1d). In these studies, we could even demonstrate aesthetic improvements to the tone wood after fungal treatment. These include a visual enhancement of the curly maple features in sycamore (famous grain variations from maple heartwood) for the bottom plate and the unintended antique texture and appearance of the Norway spruce top plate, not unlike a Cremona violin (Sedighi Gilani, Tingaut, Heeb, & Schwarze, 2014). Other positive effects on the wood due to fungal treatment are decreased density (Figure 1b,c), improved damping, enhanced sound radiation, and acoustic resistance (Sedighi Gilani & Schwarze, 2014; Sedighi Gilani, Tingaut, et al., 2014). *Physisporinus vitreus* is more active in the sapwood, that is, the region in the top plate close to the f-holes (Figure 1c). Studies on the biology of the wood-decomposing fungi helped to optimize and model the effect

of environmental factors (water activity, temperature, and pH) on hyphal growth (Fuhr, Schubert, Schwarze, & Herrmann, 2011; Fuhr, Stührk, Schubert, Schwarze, & Herrmann, 2012; Ohm et al., 2010, b). Based on analysis of our results regarding the biology of the fungi, we developed and patented a technique requiring only a 2–3 month incubation period (Table 1; Figure 1a). The reduced incubation period of 2–3 months is a technological advance enabling us to produce a second generation of biotech violins with superior acoustics in a quicker time span. Regarding the selected fungi, 20 different species of ascomycetes and basidiomycetes were screened and we found *P. vitreus* and *S. commune* to give the best results respectively for top and bottom plates (Spycher, 2008). The fungal strains were deposited at the Westerdijk Fungal Biodiversity Institute, Utrecht, The Netherlands (<http://www.wi.knaw.nl/>) for the purpose of patent procedure under the Regulations of the Budapest Treaty, with no plans for further screening of fungi.

6 | SOUND MEASUREMENTS AND PSYCHOACOUSTIC TESTS

Acoustics experts Armin Zemp and Bart van Damme at Empa are currently studying the body and sound of violins made from mycowood. Precision structure-borne sound measurements and psycho-acoustic tests with volunteers will reveal whether fungal treatment can really improve the sound of an instrument (Figure 1e). Accordingly, we made geometric clones of mycowood and untreated wood based on Computed Tomography (CT) scans of the "Caspar Hauser", an antique violin made by Guarneri del Gesù in 1724 (Anon, 2010). As part of our psychoacoustic analysis, experiments are currently being performed to assess the spread of the sound waves in the violin wood. As a musician's individual bowing style might distort the results, an electromagnet stimulates the instrument's strings for structure-borne sound measurements. Moreover, the experiment is conducted in a special acoustics laboratory, which does not reflect the outgoing sound back onto the violin. A scanning laser Doppler vibrometer then records the vibrations of the material; it measures both frequency and amplitude at around 100 random locations throughout the violin's body (Figure 1e). The latter measurements will determine the directions of waves and the pattern of their spread within the wood. Of particular interest is to compare the acoustic properties of the mycowood violins with those of the original.

Even in the run-up to these studies, the "Caspar Hauser II"—the mycowood replica—received plenty of praise (Figure 1f). Violinists who were given the opportunity to play the biotech instrument included Oleg Kaskiv, a professional soloist and Professor at the International Menuhin Music Academy in Gstaad, Switzerland. Kaskiv was immediately seduced: "The biotech violins have a warm, colorful sound comparable to the old Italian instruments." The Gstaad Festival Orchestra made a first recording of Beethoven's Violin Concerto second movement by Oleg Kaskiv on the "Caspar Hauser II" (Figure 1g). After listening to the recording (Audio S1, reproduced with permission from Walter Fischli), the Swiss soloist Andrea Saxer, a past student of the International Menuhin Music Academy, noticed that the lower and middle sound layers of the

TABLE 1 Studies on the biology and acoustic properties of mycowood

| Objective | Conclusions | Citations |
|--|--|--|
| Physical properties of mycowood | | |
| Processing wood with <i>P. vitreus</i> and <i>S. commune</i> so that it becomes acoustically similar to the wood of trees that have grown in a cold climate. | A reduction in density, accompanied by limited change in the speed of sound was recorded in mycowood. Wood with a high ratio of the speed of sound to density increases the sound emission of the instrument, meaning the plate amplitudes are high in relation to the force exciting the strings. This enhancement of resonance makes the difference between violins of average and superior quality. | Schwarze et al., 2008 |
| Influence of incubation time on the vibration and mechanics of wood treated with <i>P. vitreus</i> . | The sound radiation coefficient and the characteristic impedance in mycowood are enhanced making its appearance more brownish and resembling old wood. | Sedighi Gilani et al., 2016, Sedighi Gilani et al., 2017 |
| Fracture in Norway spruce wood treated with <i>P. vitreus</i> . | Failure load and critical stress intensity factors were reduced in mycowood after prolonged incubation periods (9–12 months). Mycowood treated for 6 months did not show any significant difference in fracture behavior compared to controls. | Sedighi Gilani et al., 2017 |
| Influence of moisture on the vibro-mechanical properties of mycowood. | Mycowood showed a greater hysteresis in moisture sorption and desorption. The tonal performance indices are improved and are less moisture dependent. | Sedighi Gilani, Tingaut, et al., 2014 |
| Hygric properties of Norway spruce and maple after incubation with <i>P. vitreus</i> . | Mycowood had a reduced density, improved dimensional stability, and a higher moisture sorption capacity. The difference in sorption behavior of early- and latewood regions were also reduced, that is, the mesoscopic hygroscopic behavior of wood is more homogeneous. | Sedighi Gilani et al., 2014 |
| Synchrotron X-ray microtomography imaging and analysis of wood degraded by <i>P. vitreus</i> | Development of an algorithm for a quantitative study of the density changes in the mycowood at different incubation periods. | Sedighi Gilani, Boone, Mader, & Schwarze, 2014 |
| Optimizing growth conditions of <i>P. vitreus</i> and <i>S. commune</i> for processing mycowood | | |
| Modeling the hyphal growth of <i>P. vitreus</i> under different environmental conditions | Development of a fungal growth model (FGA) for growth optimization of <i>P. vitreus</i> . | Fuhr et al., 2011; Fuhr, Stührk, Schubert, et al., 2012 |
| Imaging the impact of <i>P. vitreus</i> on the cell wall structure of spruce by CLSM and tomographic microscopy after Agrobacterium-mediated transformation. | 3D information obtained by CLSM and tomographic microscopy as a basis for the development of mathematical models for a more precise observation of the growth behavior of <i>P. vitreus</i> . | Fuhr, Stührk, Muench, Schwarze, & Schubert, 2012; Schubert, Stührk, Fuhr, & Schwarze, 2013 |
| Genetically decoding of <i>S. commune</i> | The genome sequence provides essential information on the lignolytic enzymes of <i>S. commune</i> . | Ohm et al., 2010 |
| Evaluation of the interspecific competitive ability of <i>P. vitreus</i> | Improvement of the uniformity of wood colonization and reduction of contaminations. | Schubert & Schwarze, 2011 |
| Process for upscaling mycowood production | | |
| Method for improving the acoustic properties of spruce tone wood. | A method for improving the acoustic properties of spruce resonance wood for musical instruments using <i>P. vitreus</i> in controlled, sterile conditions, immersed in a liquid medium enriched with fungal mycelium and containing nanofibrillated cellulose (NFC) for 2–3 months. | Schwarze, Heeb, Gilani, & Josset, 2019 |

"Caspar Hauser II" gave rise to a floating sound as sonar as a viola while the overtones resemble the voice of Maria Callas.

If the biotech violin passes all the current tests, the goal of providing superior instruments to talented young musicians with limited financial resources moves one-step closer. The eventual price of a mycowood violin is subject to demand. For instance, some Stradivari sell in excess of \$15 million while others sell for a fraction of the price. A Stradivarius made in the 1680s, or during Stradivari's "Long Pattern" period from 1690 to 1700, could be worth hundreds of thousands to several million U.S. dollars at today's prices. Depending on condition, instruments made during Stradivari's "golden period" from 1700 to about 1725 can be worth millions of dollars. In 2011, Stradivari's "Lady Blunt" violin from 1721 (named after Lord Byron's granddaughter and previous owner, Lady Anne Blunt), among the best preserved Stradivari, was sold in London for \$15.9 million in aid of the Japanese earthquake and tsunami appeal (Koh, 2011). Professional violinists pay approximately \$20,000 for contemporary instruments. Results from a recent business study in Shanghai, China by the FHS St. Gallen, Switzerland recommended a minimum price of \$30,000 for the biotech violin (FHSG, 2019).

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AUTHOR CONTRIBUTIONS

Francis Schwarze conceived the original idea and took the lead in writing the manuscript. Hugh Morris provided critical feedback and helped shape the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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