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Can upstream biofuel production increase the flow of downstream ecosystem goods and services?

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ABSTRACT

Advanced biomass feedstocks tend to provide more non-fuel ecosystem goods and services (ES) than 1st-generation alternatives. We explore the idea that payment for non-fuel ES could facilitate market penetration of advanced biofuels by closing the profitability gap. As a specific example, we discuss the Mississippi-Atchafalaya River Basin (MARB), where 1st-generation bioenergy feedstocks (e.g., corn-grain) have been integrated into the agricultural landscape. Downstream, the MARB drains to the Gulf of Mexico, where the most-valuable fishery in the US is impacted by annual formation of a large hypoxic “Dead zone.” We suggest that advanced biomass production systems in the MARB can increase and stabilize the provision of ES derived from the coastal and marine ecosystems of the Gulf-of-Mexico. Upstream, we suggest that choosing feedstocks based on their resistance or resilience to disturbance (e.g., perennials, diverse feedstocks) can increase reliability in ES provision over time. Direct feedbacks to incentivize producers of advanced feedstocks are currently lacking. Perhaps a shift from first-generation biofuels to perennial-based fuels and other advanced bioenergy systems (e.g., algal diesel, biogas from animal wastes) can be encouraged by bringing downstream environmental externalities into the market for upstream producers. In future, we can create such feedbacks through payments for ES, but significant research is needed to pave the way.

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1. Introduction

This special issue is devoted to understanding how an emerging bioeconomy will influence ecosystem goods and services [1], which have been defined as ‘*flows of natural capital to human societies*’ [2]. The US has been moving toward increased reliance on renewable energy. In addition, US agencies are considering the value of natural capital and ecosystem goods and services (ES) in planning and decision-making. According to a 2015 memorandum issued by the Obama Administration [3], integration of ecosystem goods and services into government decision-making can lead to better outcomes, fewer unintended consequences, and more-efficient use of taxpayer dollars and other resources [4].

Early ecosystem services initiatives such as the Millennium Ecosystem Assessment [5], categorized ES across four categories: provisioning, regulating, supporting and cultural. Subsequent frameworks such as The Economics of Ecosystems and Biodiversity (TEEB) and The UK National Ecosystem Assessment [2,6] recognized the need: 1) to focus on final, rather than intermediate, goods and services, 2) to use ecosystem goods and services in a comparative way (i.e. use ES to compare different scenarios, for example a proposed bioenergy scenario and a reference case), and 3) to account for the fact that different beneficiaries realize different value from ecosystem goods and services. Distinguishing final ES from intermediate ES is important when adding (‘stacking’) monetary values from various ES to compare alternative scenarios. This is because summing only final ES avoids double counting of benefits [6–8]. In addition, beneficiaries have well-defined (i.e., easily quantified) preferences for final ES, but not always for intermediate ES [9].

Freshwater ecosystems are characterized by complex ES relationships where ecosystem goods and services generated in upstream watersheds (e.g. food crops, bioenergy feedstock), can cause distant effects in downstream river networks and coastal estuaries. Hypoxia caused by the excessive use of fertilizer is a problem in coastal estuaries of the US and around the world [10], and can impact coastal economies through fisheries, property values, and tourism. A well-known example is the Mississippi and Atchafalaya River Basin (MARB), where agriculture contributes to hypoxia in the

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Gulf of Mexico [11] (Section 2). The MARB supports the majority of biofuel production in the US and has the opportunity to either exacerbate or reduce hypoxia.

This Short Communication discusses how expanding the production of perennial biofuel feedstocks using good agricultural practices upstream, and adoption of other advanced feedstocks, could influence the provision of final ecosystem goods and services from downstream coastal and marine ecosystems. We use biofuel feedstock production in the MARB as a case study to demonstrate how integrating new feedstocks into the agroecosystems and/or changing the management of current feedstocks might reduce nutrient loadings and enhance the provisioning of ecosystem goods and services downstream in the Gulf of Mexico (Section 2 and 3). Section 4 outlines how the provision of regulating ecosystem services can enable greater market penetration of advanced biofuels and Section 5 discusses how the disturbance-adapted life histories of perennial feedstocks can reduce the risk (variability) in regulating ES that they provide.

2. Linking intensive agriculture in the MARB with hypoxia in the Gulf of Mexico

If the MARB is the breadbasket of the US, the Gulf of Mexico is its fish basket. The MARB is the largest river system in North America, draining one-fifth of the landmass of the conterminous US (Fig. 1). Upstream, the MARB contains a significant fraction of the US's highly-productive agricultural land. In addition to wheat and other grains, upstream watersheds supply most of the corn and soybean used for animal feed. Downstream, the Gulf is the most productive fishery in the US [12], helping to support growing domestic and international demand for fish [13].

Hypoxia in the Gulf became an annual summertime event in the 1970s [14], and over the past four decades, nutrient loadings from MARB croplands have tripled the size of the hypoxic area in the Gulf [15,16]. Because nutrients stimulate algal growth, moderate nutrient enrichment enhances food supply for higher trophic levels that are harvested for seafood. However, when nutrient loadings are too high, they have adverse effects on fisheries. As algal blooms decompose, they deplete oxygen supplies, suffocating animals at higher trophic levels. Low-oxygen conditions stimulate phosphorus release from sediments that promote further blooms, and shunt energy into the microbial loop to decompose [17] without building populations that contribute to fisheries.

Because of hypoxia, benthic prey in the northern Gulf declined by 9.3 million tons km^{-2} y^{-1}, reducing the food base for higher trophic levels (i.e., fisheries) [18]. One-quarter of the Louisiana shelf that supports high densities of brown shrimp *Farfantepenaeus aztecus* [14] becomes uninhabitable during summer. Mobile fauna such as shrimp aggregate near the boundaries of the 'Dead zone' to escape hypoxia, where they are more susceptible to being caught [19].

The economic signals of hypoxia are challenging to detect because of strong integration with (i.e., compensation by) global markets. Recently, however, a study detected an increase in the price of large brown shrimp, which are not available from Asian markets, as a result of hypoxia [20]. In another US estuary (the Neuse River, NC), annual harvests of brown shrimp were reduced by 12.9% between 1999 and 2005 due to hypoxia [21].

The U.S. Environmental Protection Agency (EPA) Gulf Hypoxia Taskforce aims to shrink the Gulf 'Dead zone' to less than 5000 km^2 by 2035. An interim target is to reduce nutrient loadings from the MARB by 20% by 2025. Individual states are now contributing to these reduction targets by promoting better upstream agricultural nutrient management practices.

3. How can upstream biomass production benefit fisheries in the Gulf of Mexico?

Intensively managed corn and soybean agriculture is a primary cause of the Gulf of Mexico's hypoxia problem. Concerns have been raised about the effects of expanding corn production to meet the additional demand for corn-grain ethanol [22] beyond that for

Fig. 1. The Mississippi-Atchafalaya River Basin, USA, which drains to the Gulf of Mexico. Map created by Dr. Latha Baskaran (ORNL).

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animal feed. Nutrient exports to the Gulf could increase by 10–35% if bioenergy supply continues to rely on ethanol from corn grain following current fertilization practices [22]. Under prevailing intensive corn grain production to meet ethanol demand, a 15% increase in corn acreage could increase nutrient exports by 4–6% [23]. However, making the transition to growing advanced biofuel feedstocks across the MARB can help to improve downstream water quality, reduce hypoxia, and eventually benefit fisheries in the Gulf of Mexico.

Improved management of annual crops that produce ethanol from grain (corn, energy sorghum), or residues (corn stover, wheat straw, sorghum stubble) can do a great deal to reduce nutrient exports from agricultural lands in the MARB and avoid exacerbating Gulf hypoxia. Nutrient exports can be reduced through use of cover crops, riparian buffers, more precise fertilizer application, improved timing of fertilizer application, and mitigation of nutrient exports through artificial drainage (tile drains) [24,25]. Decreasing fertilizer application is most effective on tile-drained lands [26]. In addition, water-control structures are among the most effective practices for removing nitrate [27] (and to a lesser extent phosphorus) in the tile-drained Midwest US. An economic analysis showed these structures to be advantageous to growers as long as the yield penalty was small [28]. Another study used a general equilibrium model to represent the joint effects on corn and shrimp markets in the Gulf of Mexico and found that the hypoxic zone could be reduced by 11% by assessing a 3% tax on nitrogen [29] throughout the MARB, with only a 2% reduction in corn production.

Growing perennial biomass crops in lands currently used to grow annual crops or pasture, or in surrounding buffers, can improve water quality, offering in the process several other ES [30,31] (Section 4 and 5). Model simulations suggest that growing advanced biofuel feedstocks in the MARB, such as switchgrass, miscanthus, willow, and poplar (instead of current land uses), can decrease nutrient loading at the watershed scale and the scale of large river basins [32]. Model projections for the Arkansas-White-Red river basin (a tributary of the MARB) compared nutrient and sediment loadings under current and projected future agro-ecosystems dominated by switchgrass, and found a median (albeit variable) decrease in loadings among 173 large river basins [33].

Another promising option is production of biomass from animal waste and perennial grasses. The net-present value of a system with codigested dairy wastes and compressed natural gas was estimated at $40 million with environmental credits for a large dairy [34]. Finally, producing biodiesel from algal feedstocks growing in wastewater could also help decrease nutrient loadings significantly [35], but most algal biofuel options are still at the laboratory or demonstration stage of commercial development. Research to increase algal productivity and reduce costs (e.g., nutrient inputs) is needed before this source of fuel will become economically competitive [36].

4. Can ecosystem services facilitate market penetration of advanced biofuels?

Advanced biomass production systems can provide biofuel feedstock (a provisioning service) that contribute towards U.S. Renewable Fuel Standard (RFS) targets without degrading downstream aquatic ecosystems (Section 3). However, to achieve environmental and social benefits downstream, advanced biofuel production must first become economically competitive. One strategy would be to capitalize on some of the multiple other ecosystem services provided by advanced biofuels, such as carbon sequestration, water purification and pest regulation (among others) [37–39].

The production of marketable ES can potentially enhance and diversify revenue streams for advanced biomass feedstock producers [40]. Income can be derived from credits traded in environmental markets or other incentive programs such as credit for Renewable Fuel Identification Numbers, or enrollment in appropriate US Department of Agriculture Conservation Programs. These can include carbon credits [41] (for carbon sequestration services [42]), nutrient-reduction credits (for water purification services) [41], revenue from reclaiming contaminated land or water (for bioremediation services [43]), and conservation enrollment payments (for supporting service related to habitat provision). One disadvantage of government-supported PES schemes is the political uncertainty associated with future income from these sources.

If bioenergy producers could derive additional revenues from these ES, then these services can be thought of as co-products of bioenergy production. Market-based mechanisms could provide upstream producers with incentives to choose feedstocks and production systems that reduce the degradation of downstream ecosystem services (Fig. 2). By stacking credits (i.e., receiving payment for multiple final ecosystem goods and services), it may be possible to close the profit gap between the current unsustainable bioenergy production systems (e.g., corn ethanol) to more-sustainable bioenergy systems based on advanced feedstocks.

Currently markets for water purification services are rare in the US, and especially in the MARB. The Ohio River Basin Nutrient Trading Program is the only water quality program currently operating in the MARB. Most active water-quality trading programs in the US are “cap-and-trade” and focus on individual pollutants, such as nitrogen, phosphorus, or sediment. If a point-source discharging facility in the US is unable to meet its legal loading limits, it can purchase credits from a farm or forestry operation that has generated extra credits by reducing pollutant runoff through conservation practices, as long as the EPA (regulator) determines that the trading process leads to overall improvements in water quality [44]. Nutrient credits are traded based on the amount of pollutant reduced because of the adoption of a conservation practice. For example, if a wastewater treatment plant is out-of-compliance with local water standards, it can purchase credits from upstream farmers to grow perennial feedstocks that improve water quality.

The World Resources Institute conducted a feasibility study to assess the benefits and economic viability of a broader nutrient-trading program in the MARB [44]. Perez et al. [13] evaluated several scenarios and showed that credits were generated from more land and higher profits were realized when credit prices for both nitrogen and phosphorus were offered in a trading market. So long as there is a large-enough area of eligible agricultural land available upstream within the same watershed, trading is the most cost-effective way of attaining local nutrient goals [44]. One modeling study compared a ‘command-and-control’ scheme (regulatory thresholds) with a phosphorus market for the Lake Okeechobee watershed in FL [45]. The study demonstrated the theoretical possibility of selling 80% of credits (the majority purchased by dairies) to meet a cap of 30% total phosphorus reduction [45].

5. Increase resilience in ES provisioning through feedstock choice

Whereas human wellbeing depends on the actual “value” of ES, it also depends on reliable ES provision over time. This, in turn, depends on “how” and “how well” ES are buffered against disturbances [5,46]. In a review of resilience in ES, Biggs et. al. (2012) [47], recommended that critical thresholds (‘tipping points’) can be avoided by conserving regulating ES.

A bioeconomy built on disturbance-resistant perennial crops could stabilize the supply of ES including biomass for fuel.

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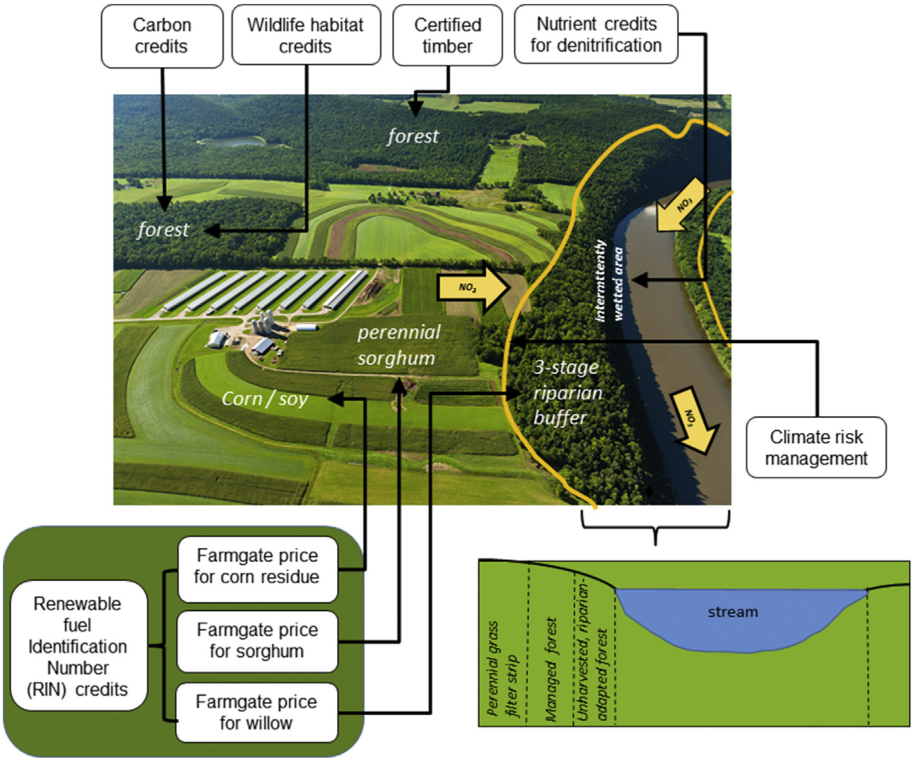

Fig. 2. Stacking of environmental credits available from a hypothetical future farm.

Perennial feedstocks (rather than annual grains) could provide insurance value [14] against climate-related hazards such as drought, flood and fire that are expected to increase in MARB [48]. By choosing perennial feedstocks, we could reap the natural capital provided by many generations of adaptation to natural disturbance.

To understand the possible insurance value of perennial feedstocks, link feedstock traits to ecosystem services. For example, Grime's [49] life history classification (the ‘C-S-R triangle’) distinguishes plant species based on allocation to three endpoint strategies (Fig. 3). Competitive species (C) tend to be long-lived trees forming a dense canopy of mesomorphic leaves aboveground and a spreading root system belowground. Stress-tolerant species (S) are conservative in the use of nutrients, water, and light, and therefore tolerate low levels of resources. Ruderal species (R) are well-adapted to colonizing disturbed habitat because they allocate more resources to reproduction (seed production).

Candidate agricultural crops tend to be fast-growing species that tolerate frequent harvest and other disturbances. Among bioenergy feedstocks, the most productive choices are ruderals (i.e., annuals) with fast growth rates. Generally, ruderal species tolerate low-intensity resource stress, but also experience high mortality when disturbed [43]. Competitor and stress-tolerant species have slower reproduction (fewer seeds) than ruderals. Although in natural settings, ruderals colonize quickly following disturbance, shortening the period of exposed soil, this is not true for ruderal feedstocks (e.g., annual row crops like corn) [50]. Annual crops such as corn, have narrow soil moisture tolerances and must therefore be planted in tile-drained fields in hydric soils and irrigated fields in arid climates.

Whereas ruderals typically respond to disturbances through resilience, perennials exemplify a strategy of resistance. Disturbance-adapted perennials maintain continuous soil cover because they are resistant to short-term climatic fluctuations. Perennial feedstocks survive episodes of adverse growing conditions by allocating energy to below-ground roots that can reach water and store carbon and nutrients [50–52]. Lowland varieties of switchgrass (*Panicum* spp.), willow (*Salix* spp.), and poplar (*Populus* spp., including cottonwoods) are well adapted to wet soils and remain viable when planted in floodplains, thereby avoiding economic and soil losses associated with intermittent flooding [53,54]. Therefore, planting selected perennial feedstocks in floodplains or riparian zones should help to hold soils and protect water quality, as well as biomass [37].

Compared to annual bioenergy feedstocks, perennial species have lower nutrient requirements and higher water-use efficiency [55], characteristic of a stress-tolerant species (Fig. 3). This conservative use of resources by perennial feedstocks reduces the risk of over-fertilization reducing freshwater pollution and potentially offering other water purification services (Section 4). Annual crops, such as corn, are not adapted to tolerate low-nutrient conditions or drought, and therefore require significant amounts of fertilizer and irrigation water, which can exacerbate water depletion and pollution (Section 2).

Many plants in the US that can be used as feedstocks are adapted to disturbance from wildfire and show a combination of ruderal and stress-tolerant traits. Examples of native US species include switchgrass [56], shortleaf pine (*Pinus palustris*), and to a lesser extent, loblolly pine *P. taeda* [57]. Miscanthus spreads through underground rhizomes, with the genus persisting within a matrix of forest disturbed by volcanic activity, landslides, and wildfire in its native range of Japan [55]. Sorghum is an annual crop that is fire-adapted and drought-tolerant that has naturalized in the US and elsewhere. Like sugarcane, sorghum stems contain sugar and are therefore easier to convert to ethanol than other cellulosic feedstocks. It is drought tolerant and is projected as a feedstock in arid parts of the MARB [58–60]. Energy sorghum is currently being hybridized with invasive Johnson grass (*Sorghum halepense*) to produce a perennial variety with improved ecological properties

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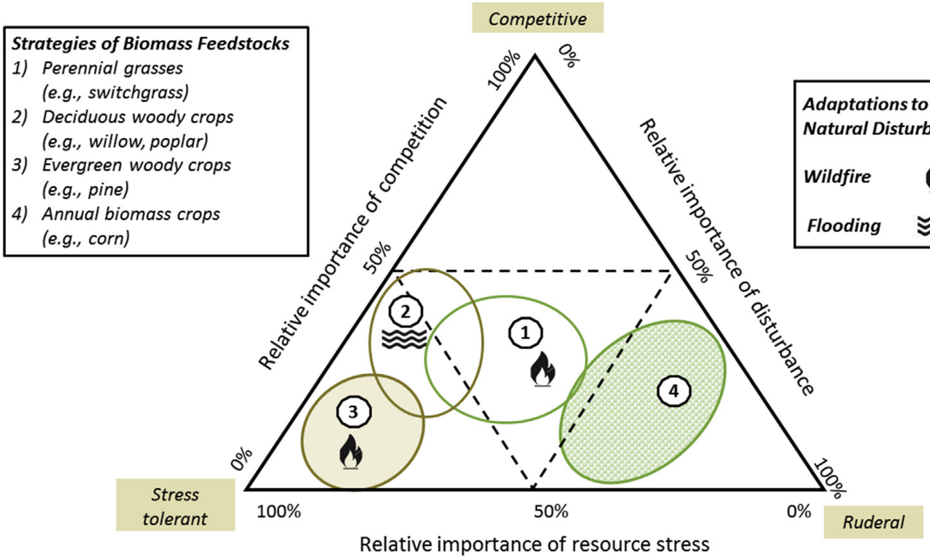

Fig. 3. Life history strategies of biomass feedstocks.

[61,62], and similar efforts are underway for wheat, sunflower and other annual crops [61].

Perennial grasses and sorghum are projected to play an increasingly important role in arid parts of the US Midwest (within the MARB) as the Ogallala aquifer becomes depleted and irrigation becomes more expensive [58–60]. Widespread adoption of disturbance-adapted perennial feedstocks with lower vulnerability to weather extremes could potentially buffer bioenergy supply chains against future climate variability [48] and water scarcity [63]. Planting feedstock mixtures could result in trait diversity that is likely to provide further ‘insurance value’ [14] by providing a mixture of species with a wider range of tolerance levels. Plant diversity can produce higher sustained yields in low-input agroecosystems [64].

6. Conclusions: knowledge gaps and research needs

This Short Communication makes the case that payment for non-fuel ES could facilitate market penetration of advanced biofuels by closing the profitability gap. The hope is that the perennialization and diversification of bioenergy landscapes in the US will increase the provision of regulating services and stabilize provisioning services. However, a significant amount of research is needed to reach this goal, including progress in the following areas:

- Identify perennial and other advanced feedstocks that can provide regulating ES and insurance value, and quantify their ability to stabilize ES provision over time in the face of environmental change;
- Identify and quantify causal relationships between upstream feedstock cultivation (or production decisions) and downstream ES;
- Communicate these causal relationships above in order to elicit accurate ES values from beneficiaries; and
- Embed bioenergy systems in broader Payment for Ecosystem Services schemes that lead to reliable ES provision and PES for biofuel producers.

Considering the above research gaps, the Gulf of Mexico example presented in this Short Communication would be challenging to study within current conceptual frameworks for ES. First current ES frameworks are static but real-world applications involve complex and dynamic causal relationships in space and time. Furthermore, the variation in the provision of ES produces risk and uncertainty that has economic consequences. In our case, the spatial displacement of downstream ES depends on upstream decisions in the MARB. Downstream research could focus on detecting economic signals from fisheries, but this activity would be challenged by high year-to-year variability and the fact that products of fisheries trade on global markets. Matching spatial scales between biophysical models to understand the consequences of upstream land-management decisions, a globally integrated fish market, and feedbacks from a MARB-wide nutrient market is a grand challenge indeed.

Some feasible advanced bioenergy production systems add ES beyond fuel, mostly regulating ES. One goal would be to incentivize the use of feedstocks that combine fast growth with regulating services to maximize the overall provision of final ES, upstream and downstream. Because traits that benefit ES tend to be related to adaptation to natural disturbances, we see a need to study how production practices can better mimic historical regimes. One outcome may be trait-based guidance to generalize from well-studied agronomic crops to other, less-well studied plants that provide similar ES portfolios. As one example, perennialization can be achieved through plant breeding. Furthermore, research is needed to design robust production systems that grow, harvest, and convert mixtures of species (non-uniform feedstocks) that together enhance the value of the ES portfolio. Research on diverse feedstocks is needed both for cellulosic agricultural crops and for algal production systems. Finally, research is needed to improve technologies (e.g., precision agriculture) that reduce over-fertilization or that make mitigation options (e.g., riparian buffers) more affordable.

The research needs described above span disciplines from plant ecology to watershed processes and river biogeochemistry, from ecology to economics, from life history theory to social sciences, from understanding what motivates biomass feedstock producers to what beneficiaries of ecosystem services are willing to pay. Furthermore, given the complexity of the system described here, we see considerable challenges to effectively communicate the cause-and-effect relationships between upstream decisions and downstream consequences. Clear communication of these

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relationships will be important in order to estimate how they are valued by stakeholders.

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