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# Site-Selective Catalytic Carboxylation of Unsaturated Hydrocarbons with CO<sub>2</sub> and Water

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**Supporting Information** 

**ABSTRACT:** A catalytic protocol that reliably predicts and controls the site-selective incorporation of  $CO_2$  to a wide range of unsaturated hydrocarbons utilizing water as formal hydride source is described. This platform unlocks an opportunity to catalytically repurpose three abundant, orthogonal feedstocks under mild conditions.

T he utilization of carbon dioxide  $(CO_2)$  and alkenes as chemical feedstocks holds promise to streamline synthetic sequences for forging C–C bonds.<sup>1</sup> In particular, the direct catalytic hydrocarboxylation of olefins with CO<sub>2</sub> represents a unique opportunity to convert abundant feedstocks into fatty acids, key building blocks in industrial endeavors.<sup>2</sup> However, major hurdles have impeded the full adaptation of such a scenario.<sup>3</sup> Although Markovnikov selectivity can be obtained with styrenes, these methods make use of air-sensitive, stoichiometric organometallic reagents (Scheme 1, path a),<sup>4</sup>

# Scheme 1. Catalytic Carboxylation of Olefins and H<sub>2</sub>O as Potential Hydride Source



or remain substrate-specific.<sup>5</sup> Extensions to abundant unactivated internal alkenes or  $\alpha$ -olefins are more problematic (Scheme 1, path b),<sup>6</sup> as noble metals, high CO<sub>2</sub> pressures and elevated temperatures are required. Additionally, the challenge of site-selectivity in these events is preeminent, invariably obtaining mixtures of carboxylic acids.<sup>6</sup> Indeed, the ability to control and fundamentally alter the effective discrimination of a catalytic CO<sub>2</sub> incorporation into unactivated olefins still remains an unanswered challenge. Recent studies from our group demonstrated that a halogenation/carboxylation sequence allowed for obtaining isomerically pure fatty acids from hydrocarbon feedstocks.<sup>4</sup> However, the need for halogenated species and activating groups for modulating the site-selectivity still constituted a daunting scenario, reinforcing a change in strategy.<sup>8</sup> Driven by the ability of some specific low-valent transition metals to generate metal hydrides (Scheme 1, bottom),<sup>9,10</sup> we questioned whether we could harness water, a renewable feedstock typically employed as proton source, as a mild, inexpensive and safe hydride precursor, thus significantly reducing the chemical footprint of traditional hydride sources used in hydrocarboxylation events (Scheme 2, top).<sup>3–6</sup> Although we

#### Scheme 2. Hydrocarboxylation Events with H<sub>2</sub>O and CO<sub>2</sub>



recognized that such a scenario might unlock an opportunity to repurpose three abundant chemical feedstocks, it was unclear whether such a strategy could be implemented, as the combination of nickel salts and water remains virtually unexplored.<sup>11</sup> If successful, we hypothesized that site-selectivity could be rationally predicted and controlled by exploiting the inherent distinct chemical reactivity of easily interconverted alkenes and alkynes<sup>12</sup> with CO<sub>2</sub> via either hydrometalation (I)<sup>13</sup> or nickelalactone formation (II) (Scheme 2, bottom).<sup>14</sup> Herein, we report our studies toward this goal, resulting in a user-friendly protocol that selectively combines three abundant chemical feedstocks under mild conditions.

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Our investigations began by evaluating the reaction of styrene with  $CO_2$  at atmospheric pressure. A judicious screening of all the reaction parameters revealed that a combination of NiCl<sub>2</sub>·6H<sub>2</sub>O (5 mol %), 4,4'-di-*tert*-butyl-6-methyl-2,2'-bipyridine (L1, 5 mol %), water (9 equiv) in DMA at 0 °C using Mn as reducing agent provided 1 in 91% isolated yield as single regioisomer.<sup>15–17</sup> In line with our expectations,<sup>7,18</sup> the reaction temperature, the amount of water and the inclusion of substituents adjacent to the nitrogen atom on the ligand backbone had a profound impact on reactivity.<sup>15</sup> Importantly, rigorous control experiments univocally revealed that the presence of both Mn and water are crucial for the generation of the catalytic active species.<sup>15</sup>

With a reliable set of conditions in hand, we then turned our attention to study the generality of our protocol (Table 1).



<sup>*a*</sup>Isolated yields, average of two independent runs. Conditions: 1a–w (0.20 mmol), NiCl<sub>2</sub>·6H<sub>2</sub>O (5 mol %), L1 (5 mol %), Mn (1.50 equiv), H<sub>2</sub>O (9 equiv), CO<sub>2</sub> (1 bar), DMA (0.5 M), 0 °C. <sup>*b*</sup>Isolated as methyl ester. <sup>*c*</sup>NiCl<sub>2</sub>·6H<sub>2</sub>O (10 mol %). <sup>*d*</sup>At rt. <sup>*e*</sup>From acetal after workup. <sup>*f*</sup>H<sub>2</sub>O (6 equiv). <sup>*g*</sup>dr = 1:1. <sup>*h*</sup>1 g scale. <sup>*i*</sup>NiCl<sub>2</sub>·glyme (10 mol %), H<sub>2</sub>O (1.1 equiv), 70 °C, NMP (0.5 M). <sup>*j*</sup>H<sub>2</sub>O (3.3 equiv). <sup>*k*</sup>S0 °C.

Comparable reactivity was found for electron-rich and electronpoor styrenes, whereas the inclusion of ortho-substituents did not hinder the reaction (2b). This method displayed excellent chemoselectivity, as silvl ethers (2k), aryl fluorides (2g, 2s, 2t), esters (2f, 2v), ketones (2l, 2m), acetals (2e, 2i) or amides (2h) could be well accommodated. The presence of boronic esters (2j) or disubstituted olefins (2d) did not interfere, suggesting the implementation of orthogonal techniques via further functionalization. The prospective potential of this technique was showcased by the preparation of nonsteroidal anti-inflammatory drugs such as Naproxen (2p), Fenoprofen (2n) or Ibuprofen (2o), the latter on a gram scale. In contrast to related styrene hydrocarboxylations,<sup>3–5</sup> this method could be extended to disubstituted styrenes by simply adjusting the amount of water and temperature, leading to quaternary carbon centers (2q-2u), or 1,2-disubstituted analogues (2v, 2w). In the latter, CO<sub>2</sub> incorporation selectively occurred adjacent to the most electron-poor arene,<sup>13</sup> the structure of which was univocally characterized by X-ray crystallography.<sup>15</sup>

Encouraged by these results, we wondered whether our protocol could be extended to industrially relevant unactivated  $\alpha$ -olefins, compounds produced on a large scale from ethylene oligomerization.<sup>19</sup> Notably, a cocktail consisting of NiI<sub>2</sub> (10 mol %) and bathocuproine (L2, 25 mol %) allowed to cleanly convert 1-hexene into 3a in 66% yield as a single regioisomer under atmospheric pressure of CO<sub>2</sub> (Table 2). These results

#### Table 2. Hydrocarboxylation of Unactivated Olefins<sup>a</sup>



(0.20 mmol), NiI<sub>2</sub> (10 mol %), bathocuproine (L2, 25 mol %), Mn (3.60 equiv), H<sub>2</sub>O (4.0 equiv), CO<sub>2</sub> (1 bar), DMF (0.25 M), 50 °C.  ${}^{b}$ H<sub>2</sub>O (6.0 equiv) and DMF (0.50 M).

are particularly remarkable taking into consideration the low selectivity profiles found in related carbonylation processes where CO was generated via reverse water-gas shift reactions at elevated temperatures with either Ru or Rh complexes.<sup>6,20</sup> As shown for 3c-3e the inclusion of arenes, esters or ketones on the side-chain did not erode the selectivity profile, obtaining exclusively linear acids. Although extending the scope to internal unactivated alkenes was expected to be rather problematic due to their lower binding affinity to metal complexes,<sup>21</sup> this was not the case. Indeed, cyclic olefins led to 3b, whereas the use of acyclic olefins, even as E/Z mixtures, resulted in the selective CO<sub>2</sub> incorporation at unfunctionalized primary sp<sup>3</sup> C–H sites en route to 3f-3j via iterative  $\beta$ -hydride elimination/migratory insertion sequences (chain-walking).<sup>21,22</sup> These observations are particularly noteworthy; indeed, the ability to use water as hydride source might significantly reduce the chemical footprint in chain-walking strategies while circumventing the need for stoichiometric organometallic reagents, halogen precursors reducing agents with high molecular weight such as organosilanes.<sup>2</sup>

Next, we surmised that the distinct reactivity of chemically interchangeable alkynes and alkenes with CO<sub>2</sub> could be turned into a strategic advantage, thus offering a method that might promote a site-selectivity switch in aliphatic side-chains. As shown in Table 3, this turned out to be the case. Although



Site-selectivity switch with internal unsaturated hydrocarbons

H Me Me	Ni / <b>L2</b>	Me Me	Ni / L2	Me
<b>CO₂H</b> 5a, 56% (l:b = 1:99)		4-octene ( <b>A</b> ) 4-octyne ( <b>B</b> )		<b>3f</b> , 50% (I:b = 99:1)

<sup>a</sup>Isolated yields, average of two independent runs. Branched: NiI<sub>2</sub> (10 mol %), L2 (25 mol %), B2nep2 (10 mol %), Mn (3.6 equiv), H2O (1.0 equiv), CO<sub>2</sub> (1 bar), DMF (0.17 M) at rt, then H<sub>2</sub> (1 bar), Pd/C (10 mol %). Linear: As Table 2. <sup>b</sup>10 mmol, 5 mol % NiI<sub>2</sub>. <sup>c</sup>NaI (1 equiv).  $^{d}$ dr = 1:1.  $^{e}$ Et<sub>3</sub>SiH (1 equiv) and RhCl(PPh<sub>3</sub>)<sub>3</sub> (6 mol %) in lieu of H<sub>2</sub>, Pd/C. <sup>f</sup>ee determined from the acrylate intermediate.

linear acids 3f, 6b-10b were exclusively formed from alkene coupling partners under a NiI<sub>2</sub>/L2 regime, a carboxylation/ hydrogenolysis event of alkyne counterparts resulted in branched products (4a-10a).<sup>24,25</sup> Notably, no significant erosion in enantioselectivity was found en route to either 10a or 10b whereas exclusive linear selectivity was found for 6b.<sup>22</sup> It is worth noting that 3f could be obtained on a large scale using 5% NiI<sub>2</sub> loading. As expected, such a regioselectivity switch was not limited to terminal alkynes or  $\alpha$ -olefins, as 5a and 3f were exclusively obtained from the corresponding internal congeners (Table 3, bottom). Collectively, the results of Tables 2 and 3

suggested that the valorization of bulk industrially relevant olefins by using inexpensive CO2 and H2O as chemical feedstocks would be within reach (Scheme 3). Gratifyingly, 3f

## Scheme 3. Carboxylation of Industrially-Relevant Olefins





could be obtained as a single regioisomer from unrefined mixtures of olefins (Scheme 3, top). Bolstered by these results, we became intrigued about the prospect of coupling ethylene, the largest-volume organic chemical produced in industry (Scheme 3, bottom).<sup>26</sup> Although preliminary, we found that propionic acid (11) could be obtained in 20 turnover numbers (TON), representing a proof of concept that could potentially pave the way to design safer alternatives to the BASF process based on hazardous  $\overline{CO}$  and  $[Ni(CO)_4]$ .<sup>2</sup>

In summary, we have designed a predictable and tunable siteselective hydrocarboxylation of a wide range of unsaturated hydrocarbons with CO<sub>2</sub> by using water as hydride source.<sup>2</sup> This method unlocks an opportunity to selectively repurpose three chemical feedstocks, including bulk industrial olefins. Although future mechanistic work is warranted to unravel the origin of both reactivity and selectivity,<sup>29</sup> we believe this study will foster new investigations for building up molecular complexity.

#### ASSOCIATED CONTENT

#### **S** Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b07637.

> Data for **2w** (CIF) Experimental procedures, crystallographic data and spectral data (PDF)

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#### Notes

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