Ni-catalyzed Reductive Carboxylation of Cyclopropyl Motifs with CO_2

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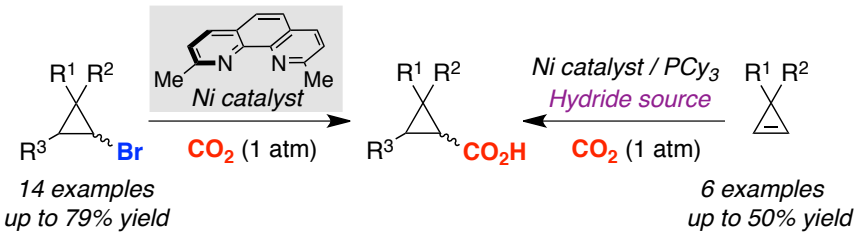

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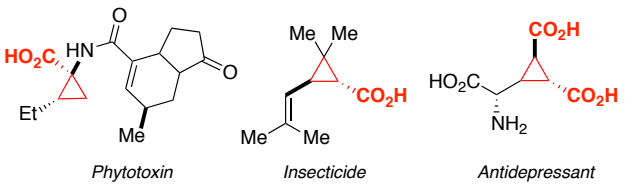
Abstract A Ni-catalyzed reductive carboxylation technique en route to cyclopropyl carboxylic acids has been developed. This user-friendly and mild transformation operates at atmospheric pressure of CO_2 and utilizes either organic halides or alkene precursors, thus representing the first example of catalytic reductive carboxylation of secondary counterparts lacking adjacent π-components.

Key words Nickel, carboxylation, cross-coupling, carbon dioxide, catalysis

Over the past few years, metal-catalyzed cross-electrophile coupling reactions of organic halides have become powerful alternatives to the well-established cross-coupling reactions based on nucleophilic/electrophilic regimes.[1] Although remarkable levels of sophistication have been reached, the vast majority of these transformations rely on the utilization of homogeneous precursors such as carbonyl compounds or organic halides, among others.[1] Indeed, the employment of heterogeneous coupling partners in these endeavors remains rather unexplored, constituting an opportunity to increase the applicability of these processes. In this context, the design of cross-electrophile coupling reactions based on the utilization of abundant and non-toxic CO_2, probably the greenest C1 source in nature,[2] represents a unique strategy to explore the ability to convert simple precursors into carboxylic acids, molecules of utmost relevance in a wide variety of molecules that display significant biological activities.[3] Unfortunately, the thermodynamic stability and kinetic inertness of CO_2 constitute serious drawbacks to be overcome when designing catalytic processes.[2] Driven by the seminal stoichiometric studies reported by Osakada,[4] we[5] and others[6] have recently developed a series of metal-catalyzed reductive carboxylation techniques *using organic (pseudo)halides as precursors*. While one might argue that this field has already reached its full potential, a close look at the developed protocols indicates otherwise. Specifically, while the carboxylation of primary organic (pseudo)halides poses no problems,[5d] the extension to secondary or tertiary motifs is rather problematic, and a solution to this challenge still remains elusive. At present, the catalytic carboxylation of secondary or tertiary organic (pseudo)halides remains limited to substrates containing adjacent π-components such as alkenes,[5c] alkynes[6d] or aromatic motifs.[5e,5g,6a,b,e,f] Challenged by such perception, we wondered whether the ring strain and orbital rehybridization of cyclopropyl rings[7] might facilitate the targeted carboxylation event of secondary cyclopropyl scaffolds, representing a new access to cyclopropyl carboxylic acids, scaffolds that are particularly prevalent in natural products and medicinally-important compounds (Scheme 1).[8] Herein, we describe the successful realization of this concept. This transformation is distinguished by its mild reaction conditions and by operating at atmospheric pressure of CO_2, thus constituting a powerful alternative to existing methodologies for preparing cyclopropane-derived carboxylic acids. Interestingly, a different stereoselectivity profile was found when employing either organic halides or cyclopropenes, respectively.

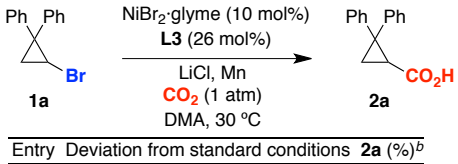
Scheme 1. Interest of cyclopropyl carboxylic acids



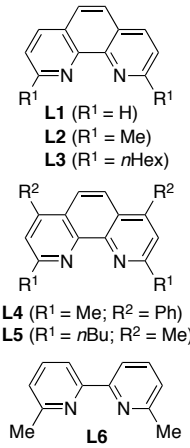
Phytotoxin *Insecticide* *Antidepressant*

We started our investigations with **1a** as model substrate. After systematic evaluation of all reaction parameters, we found that a combination of $NiBr_2$·glyme (10 mol%), **L3** (26 mol%), Mn as reducing agent, LiCl as additive in DMA at 30 ºC delivered **2a** in 77% isolated yield. Interestingly, significant erosion in yield was observed when conducting the targeted reaction at higher temperatures (entry 2), obtaining preferentially ring-opened product **3a**.[9] As shown in entries 3 and 4, precatalysts other than $NiBr_2$·glyme resulted in a remarkable lower efficiency. In contrast with other catalytic carboxylation techniques,[5b,d,e] the presence of COD did not significantly inhibit the formation of **2a** (entry 3). Although DMF provided nearly identical results than DMA (entry 6), further studies demonstrated the superior activity of DMF for less activated substrates. In line with our expectations, the utilization of MeCN, DMSO or the inclusion of Zn as reducing agent resulted in negligible amounts of **2a** (entries 5-7). Although one might argue that similar yields were found in the absence of LiCl (entry 8), its presence was crucial for avoiding the formation of **3a**. At present we do not have an explanation for such observation. In line with other reductive carboxylation techniques,[5,6] the nature of the ligand backbone exerted a profound influence on the reaction outcome. Specifically, we found that while phosphine ligands or bipyridines resulted in lower yields of **2a** (entries 14-15), phenanthroline backbones were perfectly suited for our purposes (entries 10-14). Specifically, a subtle balance of electronic and steric effects was critical for success, with ligands possessing *ortho*-alkyl motifs and lacking substituents at the *para*-position providing the best results (entries 11-13 *vs* entry 10). Control experiments revealed that all of the critical reaction parameters (Ni(II) precatalyst, **L3** and Mn) were essentially for the reaction to occur.

Table 1. Screening of the reaction conditions.[a]



Entry	Deviation from standard conditions	**2a** (%)[b]
1	None	89,77[c]
2	At 60 ºC	16
3	$Ni(COD)_2$ (10 mol%) as catalyst	75
4	$Ni(OTf)_2$ (10 mol%) as catalyst	59
5	MeCN (DMSO) as solvent	2(17)
6	DMF as solvent	89
7	Zn as reductant	11
8	No LiCl was added	80
9	Using 10% of **L3**	81
10	Using **L1** as ligand	13
11	Using **L2** as ligand	84
12	Using **L4** as ligand	58
13	Using **L5** as ligand	47
14	Using **L6** as ligand	26
15	Using PCy_3 as ligand	1
16	No $NiBr_2$·glyme or Mn	0

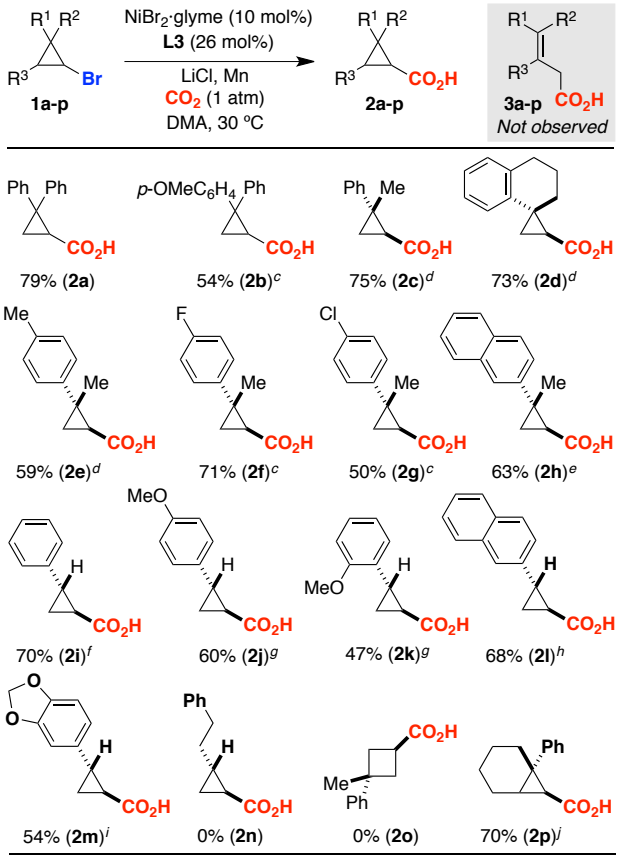


[a] Reaction conditions: **1a** (0.20 mmol), $NiBr_2$·glyme (10 mol%), **L3** (26 mol%), LiCl (0.80 mmol), Mn (0.52 mmol), CO_2 (1 atm) in DMA (0.40 M) at 30 ºC for 40 h. [b] HPLC yields using anisole as internal standard. [c] Isolated yield

With our optimized conditions in hand, we next turned our attention to explore the generality of our Ni-catalyzed reductive carboxylation of cyclopropyl bromides, precursors that are readily available in multigram quantities from known literature procedures. As shown for **2c**-**2h**, cyclopropyl backbones containing alkyl substituents provided similar reactivities to **2a**, obtaining moderate to good yields of the targeted carboxylic acids. It is worth noting, however, that the presence of aromatic substituents was required for the reaction to occur, as cyclopropyl backbones exclusively containing alkyl residues failed to react (**1n**). Likewise, we found that otherwise related cyclobutyl rings did not deliver the expected carboxylic acid **2o**; while tentative, we believe that the sp^2-like character associated to cyclopropyl rings might be critical,[7] thus allowing for a greater interaction with the nickel precatalyst and enhancing the corresponding carboxylation event. Interestingly, the reaction could be extended to monosubstituted cyclopropyl bromides (**1i-1m**), obtaining in all cases the desired products in good yields. Notably, these reaction conditions tolerated backbones containing fluorides (**2f**), chlorides (**2g**), methoxy ethers (**2b, 2j** and **2k**) or acetals (**2m**), residues that are known to participate in Ni-catalyzed cross-coupling reactions.[10] Gratifyingly, the reaction could also be extended to trisubstituted cyclopropyl bromides, as the reaction with **1p** yielded the desired product in 70% isolated yield. It is worth mentioning that all unsymmetrically-substituted cyclopropane carboxylic acids illustrated in Scheme 2 were all obtained as *cis*/*trans* mixtures. In all cases analyzed, the major isomers possessed the aromatic ring and the carboxylic acid in a *trans* motion, an observation that goes in line with other carbometalation techniques of cyclopropyl analogues.[11] Importantly, the *cis*/*trans* ratios observed do not correlate well to the ratios observed in the starting cyclopropyl bromide, suggesting that radical intermediates might come into play. Such assumption was further corroborated by reacting diastereomerically pure *trans*-**1c** and *cis*-**1c**, invariably

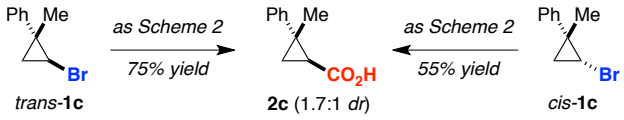
obtaining **2c** with otherwise identical *cis/trans* ratio, albeit in different yields (Scheme 3).

Scheme 2. Carboxylation of cyclopropyl bromides.[a,b]



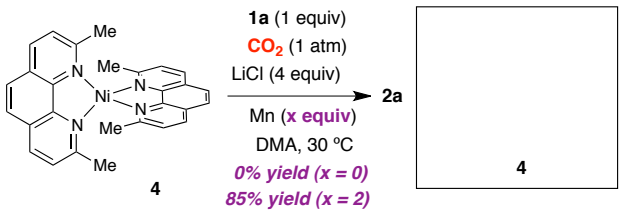
[a] Reaction conditions: **1a-p** (0.20 mmol), $NiBr_2$·glyme (10 mol%), **L3** (26 mol%), LiCl (0.80 mmol), Mn (0.52 mmol), CO_2 (1 atm) in DMA (0.40 M) at 30 ºC for 48 h. [b] Isolated yields, average of two independent runs. [c] 1.4:1 *dr*. [d] 1.7:1 *dr*. [e] 1.5:1 *dr*. [f] 5:1 *dr*. [g] 3.3:1. [h] 4.3:1 *dr*. [i] 3.6:1 *dr*. [j] 1.1:1 *dr*.

Scheme 3. Catalytic carboxylation of *trans*-**1c** & *cis*-**1c**.



Next, we focused our attention on studying the reactivity of the putative Ni(0)**L**$_2$ intermediates. While the isolation of complexes based on **L3** proved particularly cumbersome, we turned our attention to the synthesis of Ni(0)(**L2**)$_2$ (**4**)[12] as **L2** provided an otherwise analogous reactivity to that observed for **L3** (Table 1, entry 9). In line with our expectations, **4** was found to be competent as precatalyst, delivering **2a** in 66% yield. Stoichiometric experiments revealed that while the presence of 2 equivalents of Mn resulted in 85% yield of **2a**, no reaction occurred in the absence of Mn (Scheme 4). Whether this result indicates the intermediacy of Ni(I) intermediates[13] or other mechanistic scenarios is matter of ongoing studies in our laboratories.[14]

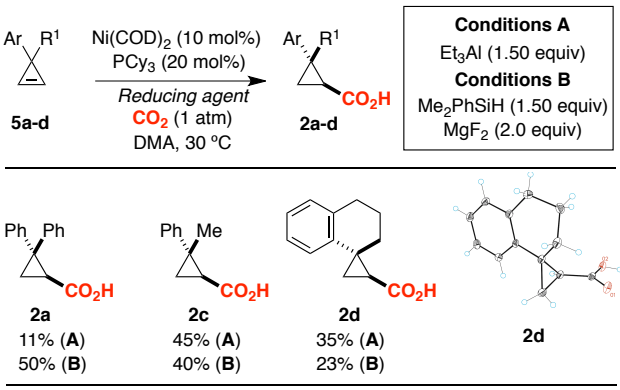
Scheme 4. Stoichiometric experiments with **4**.



While the successful preparation of cyclopropane carboxylic acids (Scheme 2) represented the first catalytic reductive carboxylation of secondary organic halides lacking adjacent π-components, the poor stereoselectivity found reinforced a change in strategy. To such end, we wondered whether the use of otherwise related cyclopropenes could promote an analogous hydrocarboxylation event with a higher stereoselectivity profile.[15] After considerable experimentation, we found that a Ni(COD)$_2$/PCy_3 regime based on the employment of Et_3Al or Me_2PhSiH as hydride sources provided the best results (Scheme 5). While moderate yields were generally observed, it is worth noting that the corresponding products **2a-d** were all obtained as single diastereoisomers. Although careful NMR spectroscopy revealed that the compounds possessed a *trans* motion, the structure of **2d** was univocally established by X-ray crystallographic analysis. While one might invoke the intermediacy of well-defined nickel hydride intermediates with a protocol based on Me_2PhSiH,[16] the successful utilization of Et_3Al in hydrocarboxylation events might suggest the intermediacy of nickelalactones followed by a subsequent transmetalation/β-hydride elimination event.[17,18]

In conclusion, a new Ni-catalyzed reductive carboxylation protocol for the synthesis cyclopropyl carboxylic acids has been developed using CO_2 as C1 synthon. This user-friendly methodology is characterized by its mild conditions at atmospheric pressure of CO_2. This work represents the first time that a catalytic reductive carboxylation of secondary organic halides can be conducted in the absence of adjacent π-components. While poor stereoselectivities were found when utilizing organic halide counterparts, the employment of otherwise related cyclopropenes resulted in single diastereoisomers. Current investigations are focused on extending the scope of these reactions and unraveling the origin of the stereoselectivities found in cyclopropene analogues.

Scheme 5. Hydrocarboxylation of cyclopropenes **4**.[a]



[a] Conditions A: **5a-d** (0.20 mmol), Ni(COD)$_2$ (10 mol%), PCy_3 (20 mol%), Et_3Al (0.30 mmol), CO_2 (1 atm) in DMA (0.40 M) at 30 ºC for 40 h. Conditions B: **5a-d** (0.20 mmol), Ni(COD)$_2$ (10 mol%),

PCy_3 (20 mol%), MgF_2 (0.40 mmol), Me_2PhSiH (0.30 mmol), CO_2 (1 atm) in DMA (0.40 M) at 30 ºC for 40 h.

Commercially available materials were used without further purification. Nickel(II) bromide ethylene glycol dimethyl ether complex ($NiBr_2$·glyme) and manganese powder (99.99% trace metal basis) were purchased from Aldrich. Anhydrous *N,N*- *N,N*-dimethylacetamideformamide (DMA, 99.8% purity) was purchased from Acros Organics. Bis(1,5-cyclooctadiene))nickel (0) ($Ni(COD)_2$, +98% purity) and tricyclohexylphosphine (PCy3) were obtained from Strem. ^1H and ^{13}C NMR spectra were recorded on a Bruker 400 MHz and 500 MHz at 20 °C. All ^1H NMR spectra are reported in parts per million (ppm) downfield of TMS and were measured relative to the signals for $CHCl_3$ (7.26 ppm), or TMS (0.00 ppm). All ^{13}C NMR spectra were reported in ppm relative to residual $CHCl_3$ (77.16 ppm), and were obtained with ^1H decoupling. Coupling constants, *J*, are reported in hertz. Melting points were measured using open glass capillaries in a Büchi B540 apparatus. Infrared spectra were recorded on a Bruker Tensor 27. Mass spectra were recorded on a Waters LCT Premier spectrometer. High Pressure Liquid Chromatographic (HPLC) analyses were performed on Agilent Technologies Model 1260 Infinity HPLC chromatography instrument equipped with Agilent Eclipse Plus C18 (3.5 um, 4.6 x 100 mm) column and UV/V is detector. Flash chromatography was performed with EM Science silica gel 60 (230-400 mesh) and using Hanessian's stain or potassium permanganate as TLC stain. The yields reported in schemes 2 and 5 refer to isolated yields and represent an average of at least two independent runs.

Ni-catalyzed carboxylation of cyclopropyl bromides 1 (scheme 2)

An oven-dried schlenk tube containing a stirring bar was charged with $NiBr_2$·glyme (0.02 mmol, 10 mol%), **L3** (0.05 mmol, 26 mol%), Mn (0.52 mmol, 2.60 equiv) and LiCl (0.80 mmol, 4 equiv). The schlenk tube was evacuated and back-filled under carbon dioxide flow (this procedure was repeated three times). Anhydrous DMA (0.50 mL) and the corresponding cyclopropyl bromide **1** (0.20 mmol, 1 equiv.) were then added under CO_2 flow. The schlenk tube was next closed at atmospheric pressure of CO_2 (1 atm) and stirred for 40 hours. The mixture was then carefully quenched with 2 M HCl to hydrolyze the resulting carboxylate and extracted several times with AcOEt and dichloromethane. The combined organic layers were dried over $MgSO_4$ and concentrated under reduced pressure. The products were purified by flash chromatography (hexanes/AcOEt).

2,2-Diphenylcyclopropanecarboxylic acid (2a).

Following the general procedure using **1a** (54.6 mg) gave **2a** as a pale yellow solid; yield: 36.7 mg (77%).

M.p.: 167-169 ºC

IR ($CDCl_3$): 3027, 1702, 1446, 1221, 903 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ 7.41-7.34 (m, 2H), 7.32-7.14 (m, 8H), 2.53 (dd, *J* = 8.0, 5.9 Hz, 1H), 2.14 (dd, *J* = 5.9, 4.8 Hz, 1H), 1.69 (dd, *J* = 8.1, 4.8 Hz, 1H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 176.6, 144.7, 139.9, 129.9, 129.7, 128.7, 128.6, 128.5, 127.7, 127.2, 126.8, 41.2, 28.7, 20.9 ppm.

Spectroscopy data match those previously reported in the literature.[19]

2-(4-Methoxyphenyl)-2-phenylcyclopropanecarboxylic acid (2b).

Following the general procedure using **1b** (60.6 mg) gave **2b** as a pale yellow solid; yield: 28.3 mg (53%); *E/Z* 1.4:1

IR ($CDCl_3$): 2954, 2929, 1698, 1511, 1245, 1176 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ 7.38-7.32 (m, 2H), 7.31-7.17 (m, 10.11H), 6.86-6.77 (m, 3.46H), 3.81 (s, 2.21H), 3.78 (s, 3H), 2.49 (ddd, *J* = 14.0, 8.0, 5.9 Hz, 1.73H), 2.11 (dd, *J* = 5.9, 4.8 Hz, 1.73H), 1.79-1.57 (m, 1.73H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 176.4, 158.6, 158.4, 145.1, 140.3, 137.0, 132.0, 130.7, 129.5, 128.9, 128.6, 128.5, 127.6, 127.1, 126.7, 114.0, 114.0, 55.4, 55.3, 40.7, 40.4, 28.8, 28.6, 21.1, 20.8 ppm.

MS (ESI-) *m/z* (%) 267 (M-H).

HRMS *calcd.* for ($C_{17}H_{15}O_3$): 267.1027, *found* 267.1030.

2-Methyl-2-phenylcyclopropanecarboxylic acid (2c).

Following the general procedure using **1c** (42.2 mg) gave **2c** as a pale yellow oil; yield: 26.8 mg (76%); *E/Z* 1.7:1.

IR ($CDCl_3$): 2958, 2928, 1695, 1443, 1427, 1224 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ 7.49-7.11 (m, 7.95H), 2.00 (dd, *J* = 8.1, 6.1 Hz, 1H), 1.95 (dd, *J* = 7.7, 5.4 Hz, 0.59H), 1.80 (t, *J* = 5.1 Hz, 0.59H), 1.59 (s, 3H), 1.55-1.45 (m, 3.59H), 1.27 (dd, *J* = 7.7, 4.6 Hz, 1H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 178.8, 177.7, 145.6, 141.3, 128.7, 128.5, 128.3, 128.3, 127.4, 126.8, 126.7, 125.8, 33.5, 32.1, 28.7, 28.1, 27.5, 21.5, 20.6, 20.1 ppm.

MS (ESI-) *m/z* (%) 175 (M-H).

HRMS *calcd.* for ($C_{11}H_{11}O_2$): 175.0765, *found* 175.0768.

3',4'-Dihydro-2'*H*-spiro[cyclopropane-1,1'-naphthalene]-2-carboxylic acid (2d).

Following the general procedure using **1d** (47.4 mg) gave **2d** as a pale yellow solid; yield: 30.8 mg (73%); *E/Z* 1.7:1.

IR ($CDCl_3$): 2929, 2861, 1690, 1430, 1224 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ δ 7.24-6.99 (m, 5H), 6.76-6.62 (m, 1H), 2.94-2.90 (m, 0.59H), 2.89 (t, *J* = 6.3 Hz, 2H), 2.16-2.09 (m, 6.24H), 2.08-1.73 (m, 6.24H), 1.67 (dd, *J* = 8.3, 5.4 Hz, 1H), 1.57 (dd, *J* = 6.5, 5.2 Hz, 1H), 1.32 (dd, *J* = 7.9, 5.5 Hz, 0.59H), 1.30-1.19 (m, 0.59H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 177.5, 176.2, 139.2, 139.1, 138.1, 134.1, 129.3, 128.5, 126.7, 126.4, 126.1, 124.8, 121.9, 35.9, 33.5, 32.2, 32.0, 30.6, 30.4, 29.5, 27.8, 23.3, 22.3, 22.0, 18.6 ppm.

MS (ESI-) *m/z* (%) 201 (M-H).

HRMS *calcd.* for ($C_{13}H_{13}O_2$): 201.0921, *found* 201.0923.

2-Methyl-2-(*p*-tolyl)cyclopropanecarboxylic acid (2e).

Following the general procedure using **1e** (45.0 mg) gave **2e** as a pale yellow oil; yield: 21.7 mg (57%); *E/Z* 1.7:1.

IR ($CDCl_3$): 2958, 2926, 1695, 1445, 1429, 1223 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ 7.21-7.16 (m, 3.25H), 7.14-7.02 (m, 3.28H), 2.33 (s, 3H), 2.32 (s, 1.88H), 1.97-1.86 (m, 1.63H), 1.75 (t, *J* = 5.0 Hz, 0.63H), 1.55 (s, 3H), 1.52-1.40 (m, 3.82H), 1.22 (dd, *J* = 7.7, 4.6 Hz, 0.63H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 178.5, 177.2, 142.8, 138.5, 136.4, 129.3, 129.2, 128.6, 127.4, 33.3, 31.9, 29.0, 28.2, 27.6, 21.6, 21.3, 21.1, 20.7, 20.3 ppm.

MS (ESI-) *m/z* (%) 189 (M-H).

HRMS *calcd.* for ($C_{12}H_{13}O_2$): 189.0921, *found* 189.0924.

2-(4-Fluorophenyl)-2-methylcyclopropanecarboxylic acid (2f).

Following the general procedure using **1f** (45.8 mg) gave **2f** as a pale yellow oil; yield: 30.3 mg (78%); *E/Z* 1.4:1.

IR ($CDCl_3$): 2958, 2928, 1697, 1512, 1429, 1220 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$) δ 7.34-7.22 (m, 3.56H), 7.09-6.94 (m, 3.28H), 1.97-1.87 (m, 1.7H), 1.76 (t, *J* = 5.1 Hz, 0.70H), 1.56 (s, 3H), 1.51-1.44 (m, 4.10H), 1.26 (dd, *J* = 7.7, 4.7 Hz, 0.70H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 178.4, 177.4, 161.8 (d, *J* = 244.8 Hz), 161.7 (d, *J* = 245.2 Hz), 141. 5 (d, *J* = 3.2 Hz), 137.2 (d, *J* = 3.2 Hz), 130.3 (d, *J* = 8.0 Hz), 129.2 (d, *J* = 8.0 Hz), 115.4 (d, *J* = 21.5 Hz), 115.3 (d, *J* = 21.3 Hz), 32.8, 31.6, 28.8, 28.3, 27.6, 21.5, 20.8, 20.5 ppm.

^{19F} NMR (376 MHz, $CDCl_3$) δ -116.1 ppm.

MS (ESI-) *m/z* (%) 193 (M-H).

HRMS *calcd.* for ($C_{11}H_{10}FO_2$): 193.0670, *found* 193.0672.

2-(4-Chlorophenyl)-2-methylcyclopropanecarboxylic acid (2g).

Following the general procedure using **1g** (49.1 mg) gave **2g** as a yellow oil; yield: 21.0 mg (50%); *E/Z* 1.4:1.

IR ($CDCl_3$): 2960, 2927, 1695, 1495, 1448, 1429 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35-7.17 (m, 6.84H), 2.05-1.91 (m, 1.71H), 1.76 (t, *J* = 5.1 Hz, 0.71H), 1.56 (s, 3H), 1.51-1.42 (m, 4.13H), 1.28-1.25 (m, 0.71H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 178.2, 177.2, 144.2, 140.0, 132.6, 132.6, 130.3, 130.2, 129.0, 128.8, 128.62 126.4, 32.9, 31.6, 28.6, 28.2, 27.6, 21.5, 20.7, 20.2 ppm.

MS (ESI-) *m/z* (%) 209 (M-H).

HRMS *calcd.* for ($C_{11}H_{10}ClO_2$): 209.0375, *found* 209.0375.

2-Methyl-2-(naphthalen-2-yl)cyclopropanecarboxylic acid (2h).

Following the general procedure using **1h** (52.2 mg) gave **2h** as a pale yellow oil; yield: 28.3 mg (63%); *E/Z* 1.5:1.

IR ($CDCl_3$): 2958, 2925, 1690, 1445, 1427, 1218 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.85-7.77 (m, 4.19H), 7.77-7.68 (m, 2.21H), 7.52-7.34 (m, 5.13H), 2.05 (dd, *J* = 8.1, 6.0 Hz, 1H), 1.99 (dd, *J* = 7.6, 5.4 Hz, 0.65H), 1.90 (t, *J* = 5.0 Hz, 0.65H), 1.63 (s, 3H), 1.60 (dd, *J* = 8.3, 4.8 Hz, 1H), 1.56-1.50 (m, 2.95H), 1.32 (dd, *J* = 7.7, 4.6 Hz, 0.65H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 178.4, 177.2, 143.1, 139.0, 133.6, 133.5, 132.6, 132.4, 128.4, 128.1, 127.9, 127.8, 127.7, 127.5, 127.0, 126.4, 126.1, 126.0, 125.9, 125.7, 33.7, 32.4, 28.9, 28.3, 27.5, 21.6, 20.9, 20.3 ppm.

MS (ESI-) *m/z* (%) 225 (M-H).

HRMS *calcd.* for ($C_{15}H_{13}O_2$): 225.0921, *found* 225.0924.

2-Phenylcyclopropanecarboxylic acid (2i).

Following the general procedure using **1i** (39.4 mg) gave **2i** as a pale yellow oil; yield: 22.8 mg (70%); *E/Z* 5.0:1.

IR ($CDCl_3$): 3029, 2927, 1689, 1445, 1231 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36-7.27 (m, 2.98H), 7.27-7.20 (m, 1.25H), 7.17-7.10 (m, 1.94H), 2.70 (td, *J* = 9.0, 7.8 Hz, 0.20H), 2.62 (ddd, *J* = 9.3, 6.7, 4.1 Hz, 1H), 2.13 (ddd, *J* = 9.2, 7.7, 5.6 Hz, 0.20H), 1.93 (ddd, *J* = 8.4, 5.2, 4.1 Hz, 1H), 1.76 (dt, *J* = 7.8, 5.3 Hz, 0.20H), 1.68 (dt, *J* = 9.5, 4.9 Hz, 1H), 1.45-1.40 (m, 1.20H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 179.6, 139.7, 136.0, 129.4, 128.7, 128.1, 127.0, 126.8, 126.4, 27.2, 26.8, 24.1, 21.6, 17.6, 12.3 ppm.

Spectroscopic data for **2j** match those previously reported in the literature.[20]

2-(4-Methoxyphenyl)cyclopropanecarboxylic acid (2j).

Following the general procedure using **1j** (45.4 mg) gave **2j** as a pale yellow solid; yield: 22.9 mg (60%); *E/Z* 3.2:1.

IR ($CDCl_3$): 2955, 2931, 1694, 1516, 1456, 1249 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22 (d, *J* = 8.2 Hz, 0.62H), 7.06 (d, *J* = 8.6 Hz, 2H), 6.88-6.75 (m, 2.62H), 3.81 (s, 3.93H), 2.69-2.61 (m, 0.31H), 2.57 (ddd, *J* = 9.2, 6.8, 4.2 Hz, 1H), 2.08 (ddd, *J* = 9.2, 7.9, 5.6 Hz, 0.31H), 1.83 (ddd, *J* = 8.3, 5.1, 4.0 Hz, 1H), 1.69 (dt, *J* = 7.7, 5.3 Hz, 0.31H), 1.63 (ddd, *J* = 9.5, 5.2, 4.5 Hz, 1H), 1.45-1.40 (m, 0.31H), 1.39-1.33 (m, 1H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 179.0, 158.5, 158.4, 131.5, 130.3, 127.9, 127.5, 114.0, 113.5, 55.3, 55.2, 26.6, 26.0, 23.5, 21.3, 17.2, 12.2 ppm.

Spectroscopic data for **2k** match those previously reported in the literature.[21]

2-(2-Methoxyphenyl)cyclopropanecarboxylic acid (2k).

Following the general procedure using **1k** (45.4 mg) gave **2k** as a white solid; yield: 18.0 mg (47%); *E/Z* 3.3:1.

IR ($CDCl_3$): 2928, 1693, 1498, 1459, 1248 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25-7.12 (m, 1.60H), 6.96-6.72 (m, 3.60H), 3.85 (s, 3H), 3.79 (s, 0.90H), 2.80 (ddd, *J* = 9.2, 7.0, 4.3 Hz, 1H), 2.58 (q, *J* = 8.5 Hz, 0.30H), 2.18-2.07 (m, 0.30H), 1.82 (dt, *J* = 7.8, 4.8 Hz, 1H), 1.67-1.54 (m, 1.30H), 1.49-1.33 (m, 1.30H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 180.4, 178.1, 158.9, 158.5, 130.5, 128.1, 127.9, 127.9, 126.2, 124.9, 120.5, 120.2, 110.5, 110.0, 55.6, 55.4, 22.7, 22.5, 22.3, 20.7, 16.3, 12.6 ppm.

Spectroscopic data for **2l** match those previously reported in the literature.[21]

2-(Naphthalen-2-yl)cyclopropanecarboxylic acid (2l).

Following the general procedure using **1l** (45.4 mg) gave **2l** as a yellow solid; yield: 18.0 mg (47%); *E/Z* 4.3:1.

IR ($CDCl_3$): 3052, 2927, 1690, 1453, 1435, 1231 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88-7.72 (m, 3.92H), 7.64-7.57 (m, 1H), 7.55-7.37 (m, 2.56H), 7.34-7.14 (m, 1.23H), 2.90-2.74 (m, 1.23H), 2.27-2.18 (m, 0.23H), 2.03 (dt, *J* = 8.7, 4.7 Hz, 1H), 1.90 (dt, *J* = 7.9, 5.4 Hz, 0.23H), 1.76 (dt, *J* = 9.5, 4.9 Hz, 1H), 1.61-1.47 (m, 1.23H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 179.5, 137.1, 133.5, 133.4, 132.7, 132.5, 128.4, 128.2, 127.9, 127.8, 127.7, 127.6, 126.5, 126.0, 125.8, 125.7, 125.1, 124.7, 29.9, 27.5, 27.0, 24.0, 17.6, 12.5 ppm.

MS (ESI-) *m/z* (%) 211 (M-H).

HRMS *calcd.* for ($C_{14}H_{11}O_2$): 211.0765, *found* 211.0769.

2-(Benzo[*d*][1,3]dioxol-5-yl)cyclopropanecarboxylic acid (2m).

Following the general procedure using **1m** (48.2 mg) gave **2m** as a yellow solid; yield: 22.6 mg (55%); *E/Z* 3.6:1.

IR ($CDCl_3$): 2924, 1689, 1504, 1442, 1233, 1038 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) δ 6.85-6.68 (m, 1.77H), 6.68-6.52 (m, 2.06H), 5.95 (s, 2.56H), 2.67-2.49 (m, 1.28H), 2.16-1.99 (m, 0.28H), 1.89-1.78 (m, 1H), 1.74-1.52 (m, 1.28H), 1.44-1.30 (m, 1.28H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 179.4, 176.9, 148.0, 147.4, 146.6, 133.5, 129.9, 122.7, 120.0, 109.9, 108.4, 108.0, 106.9, 101.2, 101.1, 27.2, 26.6, 23.8, 21.5, 17.4, 12.6 ppm.

MS (ESI-) *m/z* (%) 205 (M-H).

HRMS *calcd.* for ($C_{11}H_9O_4$): 205.0506, *found* 205.0506.

1-Phenylbicyclo[4.1.0]heptane-7-carboxylic acid (2p).

Following the general procedure using **1p** (50.2 mg) gave **2p** as a yellow solid; yield: 30.3 mg (70%); *E/Z* 1.1:1.

IR ($CDCl_3$): 2930, 1692, 1446, 1243 cm^{-1}.

^{1}H NMR (101 MHz, $CDCl_3$) δ 7.34-7.26 (m, 4.51H), 7.25-7.18 (m, 3.45H), 2.32-2.12 (m, 3.62H), 2.05 (ddd, *J* = 13.4, 8.4, 6.4 Hz, 0.75H), 1.96-1.71 (m, 5.57H), 1.66-1.15 (m, 7.74H) ppm.

^{13}C NMR (101 MHz, $CDCl_3$) δ 177. 9, 177.6, 148.9, 144.0, 128.5, 128.3, 128.2, 127.7, 126.4, 126.3, 38.2, 33.4, 32.8, 31.6, 29.2, 27.5, 26.0, 24.2, 22.7, 21.2, 21.13, 21.1, 21.0, 18.5 ppm.

Spectroscopic data for **2p** match those previously reported in the literature.[22]

Ni-catalyzed hydrocarboxylation of cyclopropenes 3 (scheme 5)

General procedure A

An oven-dried schlenk tube containing a stirring bar was charged with $Ni(COD)_2$ (0.02 mmol, 10 mol%) and PCy_3 (0.04 mmol, 20 mol%). The schlenk tube was evacuated and back-filled under carbon dioxide flow (this procedure was repeated three times). Anhydrous DMA (0.50 mL), the corresponding cyclopropene **3** (0.20 mmol, 1 equiv.) and a 1M solution of Et_3Al in hexanes (0.30 mmol, 1.5 equiv.) were then added under CO_2 flow. The schlenk tube was next closed at atmospheric pressure of CO_2 (1 atm) and stirred for 40 hours. The mixture was then carefully quenched with 2 M HCl to hydrolyze the resulting carboxylate and extracted several times with AcOEt and dichloromethane. The combined organic layers were dried over $MgSO_4$ and concentrated under reduced pressure. The products were purified by flash chromatography (hexanes/AcOEt).

Ni-catalyzed hydrocarboxylation of cyclopropenes 3 (scheme 5)

General procedure B

An oven-dried schlenk tube containing a stirring bar was charged with $Ni(COD)_2$ (0.02 mmol, 10 mol%), PCy_3 (0.04 mmol, 20 mol%) and MgF_2 (0.40 mmol, 2.0 equiv.). The schlenk tube was evacuated and back-filled under carbon dioxide flow (this procedure was repeated three times). Anhydrous DMA (0.50 mL), the corresponding cyclopropene **3** (0.20 mmol, 1 equiv.) and $HSiMe_2Ph$ (0.30 mmol, 1.5 equiv.) were then added under CO_2 flow. The schlenk tube was next closed at atmospheric pressure of CO_2 (1 atm) and stirred for 40 hours. The mixture was then carefully quenched with 2 M HCl to hydrolyze the resulting carboxylate and extracted several times with AcOEt and dichloromethane. The combined organic layers were dried over $MgSO_4$ and concentrated under reduced pressure. The products were purified by flash chromatography (hexanes/AcOEt).

***E*-2-Methyl-2-phenylcyclopropanecarboxylic acid (*E*-2c). .**

Following General procedure B using **3c** (26.0 mg) gave **2p** as a colourless oil and single stereoisomer; yield: 15.9 mg (45%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.29 (m, 1H), 7.25 – 7.18 (m, 0H), 1.99 (dd, *J* = 8.1, 6.1 Hz, 0H), 1.58 (s, 1H), 1.55 – 1.46 (m, 1H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 178.0, 145.7, 128.7, 127.6, 126.8, 32.2, 27.5, 21.6, 20.3 ppm.

***E*-3',4'-Dihydro-2'*H*-spiro[cyclopropane-1,1'-naphthalene]-2-carboxylic acid (*E*-2d).**

Following General procedure B using **3d** (31.2 mg) gave **2d** as a white solid and single stereoisomer; yield: 14.1 mg (35%).

M.p.: 162-164 ºC

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.15-7.06 (m, 3H), 6.81-6.67 (m, 1H), 2.89 (dd, *J* = 7.1, 5.6 Hz, 2H), 2.09-1.95 (m, 3H), 1.89 (dtd, *J* = 12.8, 6.5, 5.6, 3.0 Hz, 1H), 1.81 (dtd, *J* = 13.2, 7.0, 3.1 Hz, 1H), 1.68 (dd, *J* = 8.1, 5.2 Hz, 1H), 1.57 (dd, *J* = 6.5, 5.2 Hz, 1H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 176.7, 139.2, 138.2, 129.3, 126.4, 126.1, 121.9, 31.8, 30.6, 30.4, 27.8, 23.3, 22.3 ppm.

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Supporting Information

NO

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