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Iridium-catalyzed selective *N*-allylation of hydrazines

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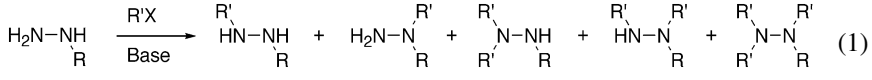
Abstract—A highly chemo- and regioselective iridium-catalyzed allylic amination is described. The reaction of various hydrazones and hydrazides with allylic carbonates proceeds at ambient temperature in the presence of an $[Ir(COD)Cl]_2$/pyridine catalyst, ammonium iodide, and diethylzinc to afford the corresponding *N*-allylation products in high yields with excellent chemo- and regioselectivities. Only the more nucleophilic nitrogen of a given hydrazine derivative undergoes the C–N bond formation to yield a branched allylic isomer as the exclusive product.

1. Introduction

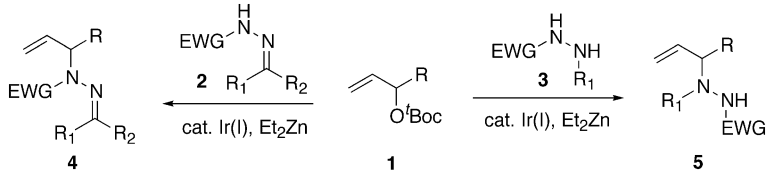
Hydrazines and their derivatives are an important class of compounds that have found wide utility in organic synthesis.[1,2] While hydrazines have traditionally been employed as reagents for the derivatization and characterization of carbonyl compounds, the N–N linkage has been used as a key structural motif of various bioactive active agents in recent years. In particular, an increasing number of N–N bond containing heterocycles and peptidomimetics have made their ways to commercial applications as pharmaceutical and agricultural agents.[3,4]



(1)

For the synthesis of substituted hydrazine derivatives, a number of methods have been developed over the years largely making use of S_N2 type displacement. These alkylative approaches, however, typically involve tedious synthetic sequences requiring extensive use of protecting groups because of the inherent difficulty in achieving selective alkylation at one of the two available nitrogens while avoiding overalkylation (Eq. 1).[3] Moreover, such methods are only applicable, for the most part, with primary electrophiles due to the lower reactivity of secondary alkyl halides and competing elimination pathways. In this regard, reductive amination[5] is particularly valuable for the installation of secondary alkyl chains, but limited only to cases where the requisite imine formation is possible. Thus, a methodology that would allow for the easy installation of branched alkyl groups to a hydrazine scaffold in one step with selectivity for a particular nitrogen would be of potential synthetic value.

Our approach to the selective alkylation of hydrazines is the formation of the C–N bond using η^3-allylmetal chemistry as outlined in Scheme 1.[6–13] Based on findings in zinc(II) alkoxide mediated allylic etherification reactions,[14,15] we wondered whether the 'zinc effect' would also be viable for the *N*-allylation reactions of hydrazones **2** and hydrazides **3**.



Scheme 1. Strategy for *N*-allylation of hydrazones and hydrazines.

Keywords: Iridium; Catalysis; Hydrazones; Hydrazides; Hydrazines; Amination; Allylation.
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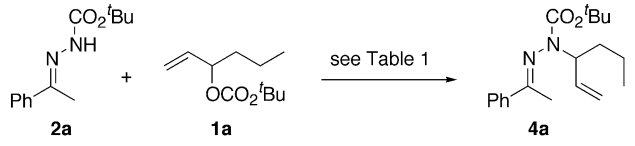
Although our prior work on allylic etherification exploited palladium catalysis, we chose to explore the use of an iridium catalyst for this endeavor, as such catalysts had been shown to exhibit a pronounced regiochemical preference for the formation of branched products.[16–19] It was also hoped that the use of diethylzinc as a basic mediator in this reaction would overcome the inherent problem of chemoselectivity, allowing for the selective delivery of an allylic electrophile to one nitrogen over the other (*N* vs *N′*-allylation). Described herein are our results towards meeting these challenges.

2. Results and discussion

Initial studies were focused on the model reaction between acetophenone-derived hydrazone **2a** and allylic carbonate **1a**, in which various reaction parameters were probed to identify an effective catalytic system (Table 1). Guided by literature precedents,[12,16,18] we chose $[Ir(COD)Cl]_2$ as the precatalyst while employing pyridine and Et_2Zn as the ligand and base, respectively.[20] Gratifyingly, these conditions adopted from our previous studies on allylic etherification proved effective to give rise to the desired *N*-allylation product **4a** with complete regioselectivity (entry 1). While THF was found to be an optimal solvent, a set of control experiments clearly indicated the importance of each component of the reaction system (entries 3–6), in which the effect of 1 equiv of NH_4I on the yield of the reaction was particularly noteworthy.[21]

Table 1. Development of Ir-catalyzed *N*-allylation of hydrazones[a]



2a **1a** **4a**

Entry	$[Ir(COD)Cl]_2$/ pyridine	Et_2Zn (equiv)	NH_4I (equiv)	% Yield
1	2.5 mol%/5 mol%	0.5	1.0	76
2[b]	5.0 mol%/10 mol%	0.5	1.0	89
3	2.5 mol%/5 mol%	0.5	—	12
4	2.5 mol%/5 mol%	—	1.0	0
5	2.5 mol%/5 mol%	—	—	0
6	—	0.5	1.0	0

[a] All reactions were performed at 25 °C in THF (0.4 mL) with 0.30 mmol (1.5 equiv) of **2a** and 0.20 mmol (1.0 equiv) of **1a**.
[b] No reaction in dioxane. 40% yield in MeCN.

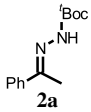
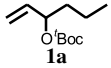
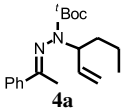
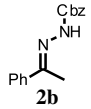
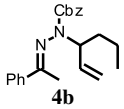
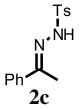
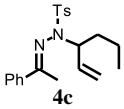
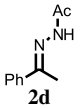
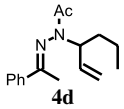
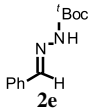
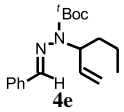
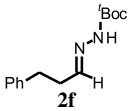
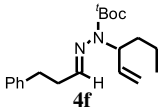
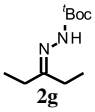
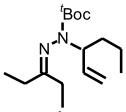
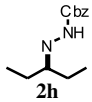
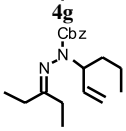
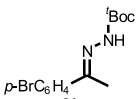
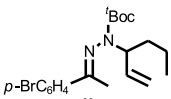
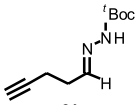
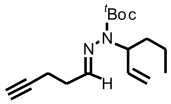
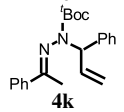
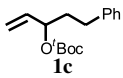
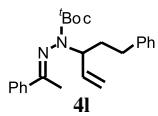
With conditions for the allylic amination established, we further examined the scope of the reaction with a wide range of substrates. As illustrated in Table 2, a variety of hydrazones derived from ketones and aldehydes participated well in the reaction. In addition to the *t*-Boc-protected hydrazone **2a** used in the initial study, both Cbz- and Ts-protected hydrazones **2b** and **2c** also proved competent reaction partners (entries 2, 3 and 8). Interestingly, the reaction of acetate **2d** worked poorly under these conditions, giving the product only in low yield as the main component of an inseperable mixture of products (entry 4). The presence of an electron withdrawing group was necessary, as substrates lacking one, such as simple phenylhydrazones, were unreactive (data not shown). The reaction tolerated an aryl bromide (**2i**) and a terminal alkyne (**2j**), and also fared well with an aromatic allylic carbonate (**1b**). Most notably, only the branched isomer of the desired product was formed in all cases examined.

Encouraged by the results of hydrazones, we endeavored to explore the feasibility of using the same catalytic system for the allylation of hydrazide **3a**. As summarized in Table 3, the desired *N*-allylation product **5a** could be obtained as a single regioisomer, with substitution at the primary nitrogen (*N′*-position). In all cases, little to no dialkylation was observed. In contrast to the reaction of hydrazones, the use of only 0.25 equiv of Et_2Zn, instead of 0.50 equiv, provided a higher yield (entries 1 vs 2). There was a substantial background reaction (13%) in the absence of Et_2Zn, presumably due to the greater nucleophilicity of hydrazides relative to hydrazones (entry 3), while the iridium catalyst was indispensable for the reaction (entry 6). In order to test the possibility that the latent nucleophilicity of the hydrazide might be sufficient to promote the alkylation without recourse to Et_2Zn as base, the reaction was performed under zinc free conditions (entries 7 and 8). Although the use of simple bases, Cs_2CO_3 and *i*-Pr_2NEt, improved the yield by a marginal amount relative to the background reaction (entries 3 vs 7 and 8), the lack of substantial reactivity highlighted the unique nature and role of Et_2Zn in this reaction.

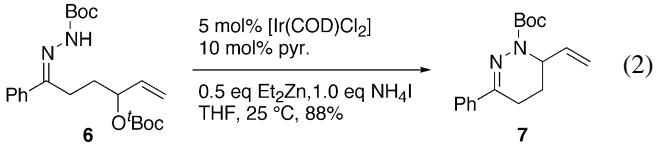
Having established working conditions, we surveyed the scope of the reaction with a variety of hyrazines and allylic carbonates (Table 4). Similar to the reaction of hydrazones, the *t*-Boc-, Cbz- and Ts-protected hydrazines **3a**, **3b** and **3c** participated well in the reaction, while the acetate-protected hydrazine **3d** failed to react under these conditions (entry 4). Also in accord with the hydrazones, hydrazines lacking an electron withdrawing substituent gave no reaction under these conditions. Good yields were uniformly obtained in the reactions of structurally diverse allylic carbonates and hydrazides (entries 5–8). In particular, it was noteworthy that a highly selective (*N* vs *N′*) allylation of *N*-acyl-*N′*-alkyl hydrazines could be achieved to form *N′*,*N′*-dialkyl hydrazides, although dialkylation was not observed to any serious extent in other reactions (entries 1–6 vs 7 and 8).

The new method was further extended to the synthesis of N–N bond-containing heterocycles via an intramolecular *N*-allylation reaction. Compound **6**, containing hydrazone and allylic carbonate moieties within the same molecule, was thus prepared (Scheme 2, vide infra) and tested for ring closure (Eq. 2). Upon subjection to our standard reaction conditions, hydrazone **6** underwent a smooth cyclization to give rise to the desired tetrahydropyridazine **7** in 88% yield. Finally, the utility of the *N*-allylated products was briefly explored through several transformations (Eqs. 3–5). Hydrazone **4h**, originally derived from acetophenone, could be converted to hydrazines **10** and **11** by standard hydrolysis[22] and reductive amination[5,23] reactions, respectively. Simple hydrogenation[25] of **4g** furnished the fully saturated *N*,*N′*-dialkyl hydrazide **12**.

Table 2. Ir(I)-Catalyzed *N*-allylation of hydrazones with allylic carbonates[a]

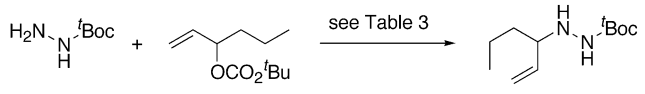
Entry	Hydrazone	Allylic carbonate	Product	%Yield
1	 **2a**	 **1a**	 **4a**	89
2	 **2b**	**1a**	 **4b**	86
3	 **2c**	**1a**	 **4c**	92
4	 **2d**	**1a**	 **4d**	17
5	 **2e**	**1a**	 **4e**	88
6	 **2f**	**1a**	 **4f**	82
7	 **2g**	**1a**	 **4g**	86
8	 **2h**	**1a**	 **4h**	75
9	 **2i**	**1a**	 **4i**	41
10	 **2j**	**1a**	 **4j**	71
11	**2a**	 **1b**	 **4k**	90
12	**2a**	 **1c**	 **4l**	83

[a] All reactions performed at room temperature in THF (0.4 mL) with 0.30 mmol (1.5 equiv) of hydrazone, 0.20 mmol allylic carbonate, 0.15 mmol of Et_2Zn (0.50 equiv with respect to hydrazone), 0.20 mmol of NH_4I (1.0 equiv with respect to electrophile), 5 mol% $[Ir(COD)Cl]_2$, and 10 mol% pyridine.



(2)

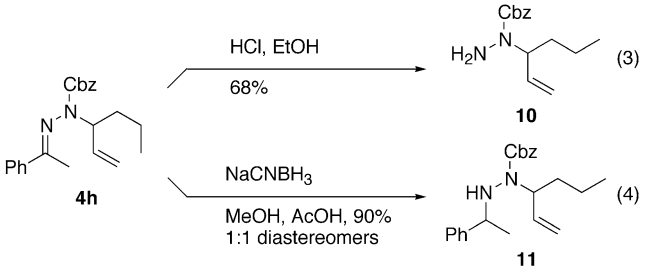
Table 3. Development of Ir-catalyzed *N*-allylation of hydrazines[a]



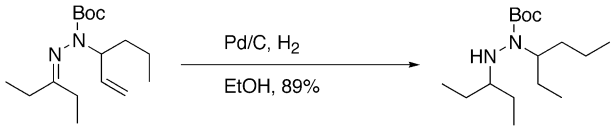
3a **1a** **5a**

Entry	[Ir(COD)Cl]$_2$/ pyridine	Et_2Zn (equiv)	NH_4I (equiv)	% Yield
1	5.0 mol%/10 mol%	0.50	1.0	74
2	5.0 mol%/10 mol%	0.25	1.0	93
3	2.5 mol%/5 mol%	—	1.0	13
4	2.5 mol%/5 mol%	0.50	—	<2
5	2.5 mol%/5 mol%	—	—	<2
6	—	0.50	1.0	0
7[b]	5.0 mol%/10 mol%	—	1.0	19
8[c]	5.0 mol%/10 mol%	—	1.0	19

[a] All reactions were performed at 25 °C in THF (0.4 mL) with 0.20 mmol of **1a** and 0.30 mmol (1.5 equiv) of **3a**.
[b] Cs_2CO_3 (1.0 equiv) was used as base.
[c] Diisopropylethylamine (1.0 equiv) was used as base.



4h **10** **11** (3) (4)



4g **12** (5)

3. Conclusion

In summary, we have developed a highly chemo- and regioselective iridium-catalyzed method for the *N*-allylation of hydrazones and hydrazines with allylic carbonates. The reaction provides the branched, *N*-allylated products in good yields under mild reaction conditions. Crucial to the success of the reaction is the utilization of diethylzinc as base, as well as ammonium iodide as a halide additive. The amination reactions of hydrazones and hydrazides described herein can provide rapid access to differentially substituted hydrazines without recourse to protecting group manipulation. Such expedient access to these compounds may be useful in further applications, such as the preparation of novel peptidomimetics or heterocycles.

4. Experimental

4.1. General

Unless otherwise noted, all reactions were conducted in

Table 4. Ir(I)-Catalyzed *N*-allylation of hydrazines with allylic carbonates[a]

Entry	Hydrazine	Electrophile	Product	%Yield
1	**3a**	**1a**	**5a**	93
2	**3b**	**1a**	**5b**	86
3	**3c**	**1a**	**5c**	57
4	**3d**	**1a**	**5d**	0
5	**3a**	**1b**	**5e**	88
6	**3a**	**1d**	**5f**	82
7	**3e**	**1a**	**5g**	85
8	**3f**	**1a**	**5i**	82

[a] All reactions performed at room temperature in THF (0.4 mL) with 0.30 mmol (1.5 equiv) of hydrazine, 0.20 mmol allylic carbonate, 0.075 mmol of Et_2Zn (0.25 equiv with respect to hydrazine), 0.20 mmol of NH_4I (1.0 equiv with respect to electrophile), 5 mol% [Ir(COD)Cl]$_2$, and 10 mol% pyridine.

flame-dried glassware under an argon atmosphere using anhydrous solvent (either distilled or passed through an activated alumina column or activated molecular sieves column). Commercially available reagents were used without further purification. Thin layer chromatography (TLC) was performed using EM Science silica gel 60 F254 plates and visualized using UV light, anisaldehyde, ceric sulfate or potassium permanganate stains. Flash chromatography was performed on EM Science silica gel 60 (40–63 μm) using the indicated solvent system. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$, unless otherwise noted, on a Varian Mercury 300 MHz, a Varian Inova 400 MHz or a Varian Inova 500 MHz spectrometer. Chemical shifts in ^{1}H NMR spectra were reported in parts per million (ppm) on the δ scale from an internal standard of residual chloroform (7.27 ppm). Data for ^{1}H NMR are reported as follows: chemical shift, multiplicity (s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet), coupling constant in Hertz (Hz), and integration. Data for ^{13}C NMR spectra are reported in terms of chemical shift in ppm from the central peak of $CDCl_3$ (77.23 ppm). Infrared (IR) spectra were recorded on a Nicolet 730 FT-IR spectrometer and reported in frequency of the absorption (cm^{-1}). High resolution mass spectra (HRMS) were obtained from the Princeton University Mass Spectrometry Facility and UCR Mass Spectrometry Facility.

4.2. Representative procedure for the preparation of hydrazones

To a suspension of *t*-butyl carbazate (5.4 g, 41 mmol) in hexanes (50 mL) was added acetophenone (7.2 mL, 61 mmol) dropwise. The reaction mixture was then heated to reflux for 8 h. After cooling to ambient temperature, the resulting precipitate was collected by suction filtration, washed with additional cold hexanes, and allowed to air dry under aspiration to afford the known hydrazone **2a**[24] (8.8 g, 91%). Other known hydrazones **2c**,[25] **2d**,[26] **2e**,[27] **2f**,[28] and **2g**[28] were also prepared following this procedure.

4.2.1. *N′*-(1-Phenyl-ethylidene)-hydrazinecarboxylic acid benzyl ester (2b). Following the same procedure as **2a**, the reaction of benzylcarbazate (831 mg, 5.0 mmol) with acetophenone (901 mg, 7.5 mmol) in hexane (10 mL) gave hydrazone **2b** (1.1 g, 98%). Recrystallization from EtOH gave analytically pure hydrazone **2b** as flocculent white crystals (1.06 g, 79%). Mp 134–135 °C. IR (film) 3200, 3050, 1700, 1730, 1540, 1230 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.92 (br s, 1H), 7.79 (m, 2H), 7.46 (m, 2H), 7.42 (m, 6H), 5.32 (br s, 2H), 2.22 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.8, 149.1, 138.2, 136.2, 129.5, 128.9, 128.7, 128.6, 126.6, 67.8, 13.2; HRMS (DEI-MS) [M^+] Calcd for $C_{12}H_{16}N_2O_2$ 268.1212, found 268.1205.

4.2.2. *N′*-(1-Ethyl-propylidene)-hydrazinecarboxylic acid benzyl ester (2h). Following the same procedure as **2a**, the reaction of benzylcarbazate (0.83 g, 5.0 mmol) with 3-pentanone (0.79 mL, 0.65 g, 7.5 mmol) in hexane (10 mL) gave hydrazone **2h** (1.1 g, 98%) as a white solid. The product was used without further purification. Mp 39–43 °C. IR (film) 3250, 2970, 1720, 1530, 1460, 1230, 1040 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.70 (s, 1H), 7.39 (m, 5H), 5.25 (s, 2H), 2.35 (q, J=8.0 Hz, 2H), 2.20 (q, J=8.0 Hz, 2H), 1.14 (t, J=7.5 Hz, 3H), 1.10 (t, J=8.0 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 159.8, 154.2, 136.2, 128.8, 128.7, 128.6, 67.6, 30.2, 21.6, 11.3, 9.8; HRMS (DCI-MS) [M+] Calcd for $C_{13}H_{19}N_2O_2$ 235.1447, found 235.1442.

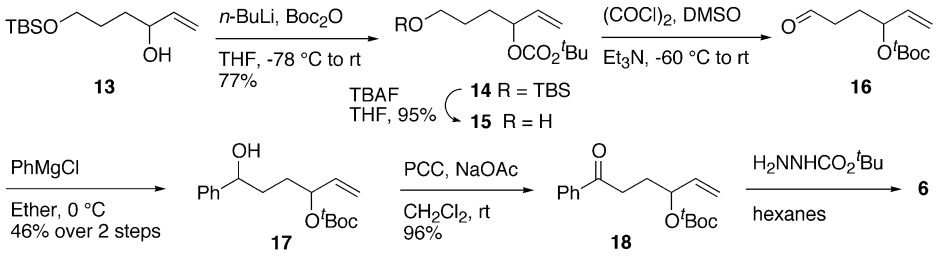
4.2.3. *N′*-[1-(4-Bromo-phenyl)-ethylidene]-hydrazinecarboxylic acid *t*-butyl ester (2i). Following the same procedure as **2a**, the reaction of *t*-butyl carbazate (661 mg, 5.0 mmol) with *p*-bromoacetophenone (1.49 g, 7.5 mmol) in hexane (10 mL) gave hydrazone **2g** (1.07 g, 68%) as a white solid after recrystallization from EtOH. Mp 167–168 °C. IR (film) 3190, 2980, 1730, 1700, 1530, 1140 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.76 (br s, 1H), 7.62 (d, J=6.8 Hz, 2H), 7.45 (d, J=7.6 Hz, 2H), 2.13 (s, 3H), 1.51 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.8, 146.3, 137.1, 131.6, 128.0, 123.6, 81.8, 28.5, 12.6; HRMS (DCI-MS) [M+] Calcd for $C_{13}H_{18}N_2O_2Br$ 313.0552, found 313.0540.

4.2.4. *N′*-Pent-4-ynylidene-hydrazinecarboxylic acid *t*-butyl ester (2j). To a solution of hex-5-ynal[29] (192 mg, 2.0 mmol) was added *t*-butyl carbazate (264 mg, 2.0 mmol). The reaction mixture was allowed to stir at room temperature until deemed complete by TLC. At this time, the reaction mixture was diluted with EtOAc, dried over Na_2SO_4, and concentrated in vacuo. Purification of the crude material by chromatography on deactivated (Et_3N) silica gel (4:1, then 2:1 hexanes/EtOAc), gave the desired hydrazone **2j** (172 mg, 41%) as a white crystalline solid. Mp 93–95 °C. IR (film) 3291, 3248, 3046, 2979, 2932, 1707, 1537, 1368, 1251, 1167 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.86 (br s, 1H), 7.25 (t, J=5.0 Hz, 1H), 2.50 (m, 2H), 2.39 (m, 2H), 1.97 (t, J=2.4 Hz, 1H), 1.47 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 152.7, 145.1, 83.0, 81.4, 69.6, 31.2, 28.5, 16.4; HRMS (DCI-MS) [M+] Calcd for $C_{10}H_{17}N_2O_2$ 197.1290, found 197.1292.

4.3. General procedure for the preparation of allylic carbonates

To a solution of allylic alcohol in dry THF at −78 °C was added *n*-BuLi dropwise. After stirring for 30 min, a solution of Boc_2O in THF was added. The reaction mixture was allowed to warm to room temperature, and was then quenched with saturated aqueous NH_4Cl. The aqueous layer was extracted with EtOAc, and the combined organic phases were washed with water and brine, dried over Na_2SO_4, and concentrated in vacuo. Purification by flash column chromatography gave the pure allylic carbonates **1a–c**.[30]

4.3.1. Carbonic acid *t*-butyl ester 1,1-dimethyl-allyl ester (1d). Following the general procedure, the reaction of 2-methyl-but-3-en-2-ol (1.78 g, 20.7 mmol) with Boc_2O (4.51 g, 20.7 mmol) and *n*-BuLi (2.5 M in hexane, 9.1 mL, 22.7 mmol) in dry THF (40 mL) gave the desired allylic carbonate **1d** (2.75 g, 71%) as a clear, colorless oil. IR (film) 2982, 2936, 1741, 1368, 1285, 1126 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 6.13 (dd, J=17.5, 11.0 Hz, 1H), 5.21 (d, J=18.0 Hz, 1H), 5.14 (d, J=11.0 Hz, 1H), 1.51 (s, 3H), 1.49 (s, 9H), 1.47 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$):



Scheme 2. Preparation of hydrazone **6**.

δ 152.1, 142.5, 113.2, 81.7, 81.6, 28.1, 26.6; LRMS (EI) *m/z* 130 (53), 85 (33), 71 (100).

4.3.2. Carbonic acid *t*-butyl ester 4-(*t*-butyl-dimethyl-silanyloxy)-1-vinyl-butyl ester (14). To a solution of 6-(*t*-butyl-dimethyl-silanyloxy)-hex-1-en-3-ol[31] (**13**, 5.9 g, 26 mmol) in dry THF (25 mL) under argon at −78 °C was added *n*-BuLi (2.5 M in hexane, 11.3 mL, 28 mmol) dropwise. After stirring 3 min, a solution of Boc_2O (5.6 g, 26 mmol) in THF (25 mL) was added. The reaction was allowed to proceed at −78 °C for 30 min, and then the ice bath was removed. On warming to room temperature, the reaction was quenched with saturated NH_4Cl, and the bulk of the THF was concentrated in vacuo. The remaining phases were partitioned between EtOAc and water, and the aqueous layer was extracted with additional EtOAc. The combined organic layers were washed with H_2O and brine, dried over Na_2SO_4, and concentrated in vacuo. The resulting crude oil was purified by chromatography (hexane/EtOAc, 40:1→20:1) to give the desired allylic carbonate **14** (6.6 g, 77%) as a colorless, sticky oil. IR (film) 3087, 2955, 2858, 1742, 1276, 1235, 1169, 1100 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 5.77 (ddd, J=17.2, 10.4, 6.4 Hz, 1H), 5.25 (d, J=17.2 Hz, 1H), 5.16 (d, J=10.8 Hz, 1H), 4.98 (q, J=6.7 Hz, 1H), 3.60 (m, 2H), 1.67 (m, 1H), 1.54 (m, 2H), 1.45 (s, 9H), 0.86 (s, 9H), 0.01 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.2, 163.6, 117.3, 82.1, 78.0, 62.8, 30.9, 28.5, 28.0, 26.1, 18.5, −5.1.

4.3.3. Carbonic acid *t*-butyl ester 4-hydroxy-1-vinyl-butyl ester (15). To a solution of allylic carbonate **14** (6.5 g, 20 mmol) in dry THF (20 mL) under argon was added TBAF (1.0 M in THF, 25 mL, 25 mmol). The reaction was complete (by TLC) after 4 h, at which time saturated NH_4Cl was added. The aqueous layer was then extracted with EtOAc, and the combined organic layers were then washed with H_2O and brine, dried over Na_2SO_4, and concentrated in vacuo to give a crude oil. Purification by chromatography (hexane/EtOAc, 4:1→2:1) gave primary alcohol **15** (4.0 g, 95%) as a clear, colorless oil. IR (film) 3363, 2981, 2937, 2874, 1740, 1370, 1277, 1255, 1163 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 5.78 (ddd, J=17.2, 10.4, 6.8 Hz, 1H), 5.26 (d, J=17.2 Hz, 1H), 5.17 (d, J=10.4 Hz, 1H), 5.00 (q, J=6.8 Hz, 1H), 3.64 (q, J=6.0 Hz, 1H), 1.5–1.8 (m, 4H), 1.45 (s, 9H), 1.42 (t, J=5.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.3, 117.4, 82.3, 77.8, 62.6, 30.8, 28.4, 28.0.

4.3.4. Carbonic acid *t*-butyl ester 4-oxo-1-vinyl-butyl ester (16). To a solution of oxalyl chloride (0.74 mL, 8.5 mmol) in dry DCM (20 mL) under argon at −60 °C was added a solution of DMSO (1.2 mL, 17 mmol) in DCM (5 mL). After 5 min, a solution of the alcohol **15** (1.5 g, 6.8 mmol) in DCM (10 mL) was added. After a further 15 min, Et_3N (3.7 mL, 34 mmol) was added, and the reaction mixture then allowed to warm to room temperature. H_2O was then added, and the aqueous layer was extracted with additional DCM. The combined DCM layers were successively washed with 0.1 M HCl, H_2O, saturated $NaHCO_3$, H_2O, and brine; dried over Na_2SO_4; and concentrated in vacuo to give aldehyde **16** (1.40 g, 96%) as an orange oil. The crude product was used without further purification in the subsequent Grignard addition. IR (film) 2928, 2936, 2826, 2727, 1740, 1370, 1275, 1255, 1163 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 9.77 (s, 1H), 5.77 (ddd, J=17.1, 10.5, 6.3 Hz, 1H), 5.30 (d, J=17.4 Hz, 1H), 5.22 (d, J=10.5 Hz, 1H), 5.04 (q, J=6.1 Hz, 1H), 2.54 (t, J=7.4 Hz, 2H), 1.98 (q, J=7.0 Hz, 2H), 1.48 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 201.2, 153.0, 135.7, 117.9, 82.5, 76.8, 39.6, 28.0, 26.6.

4.3.5. Carbonic acid *t*-butyl ester 4-hydroxy-4-phenyl-1-vinyl-butyl ester (17). To a solution of the crude aldehyde **16** (1.4 g, 6.5 mmol) in dry Et_2O (7 mL) under argon at 0 °C was added PhMgCl (1.8 M in THF, 4.5 mL, 8.2 mmol) dropwise. The reaction was completed within 15 min (by TLC), and then quenched by addition of saturated NH_4Cl. The aqueous layer was extracted with EtOAc, and the combined organic phases were washed with H_2O, saturated $NaHCO_3$, H_2O, and brine; dried over Na_2SO_4; and concentrated in vacuo to give a crude yellow oil. Purification by chromatography (hexanes/EtOAc, 7.5:1→5:1) gave the desired alcohol **17** (0.91 g, 46% over 2 steps) as a clear, colorless oil. The alcohol was characterized as a mixture of diastereomers. IR (film) 3416, 2980, 2934, 2868, 1739, 1369, 1276, 1255, 1162 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.31 (m, 4H), 7.25 (m, 1H), 5.74 (ddd, J=17.2, 10.8, 6.8 Hz, 1H), 5.23 (d, J=17.6 Hz, 1H), 5.16 (d, J=10.4 Hz, 1H), 5.15 (d, J=10.4 Hz, 1H; diastereomer), 5.00 (m, 1H), 4.66 (m, 1H), 1.95 (d, J=3.6 Hz, 1H), 1.65–1.85 (m, 3H), 1.60 (m, 1H), 1.45 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.2, 144.6, 136.3, 128.7, 127.8, 126.0 (diastereomer), 126.0, 117.5, 82.2, 78.0, 77.7 (diastereomer), 74.4, 74.3 (diastereomer), 34.8, 34.5 (diastereomer), 30.8, 30.6 (diastereomer), 28.0.

4.3.6. Carbonic acid *t*-butyl ester 4-oxo-4-phenyl-1-vinyl-butyl ester (18). To a suspension of PCC (436 mg, 2.0 mmol) and NaOAc (33 mg, 0.40 mmol) in DCM (2 mL) was added a solution of alcohol **17** (394 mg, 1.35 mmol) in DCM (2 mL). After 1 h, an additional 145 mg of PCC was added, and the stirring was continued

for an hour before 20 mL of Et_2O was added. The reaction mixture was then filtered through florisil and concentrated in vacuo to give the crude ketone **18** (377 mg, 96%) as a clear, colorless oil. This material was used for the next reaction without further purification. IR (film) 3087, 3082, 2980, 2934, 1740, 1688, 1369, 1275, 1255, 1161 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.95 (d, $J=7.8$ Hz, 2H), 7.56 (t, $J=7.4$ Hz, 1H), 7.45 (t, $J=7.6$ Hz, 2H), 5.84 (ddd, $J=17.1$, 10.5, 6.3 Hz, $J=1H$), 5.32 (d, $J=17.1$ Hz, 1H), 5.23 (d, $J=10.5$ Hz, 1H), 5.13 (q, $J=6.3$ Hz, 1H), 3.06 (t, $J=7.5$ Hz, 2H), 2.12 (q, $J=7.1$ Hz, 2H), 1.47 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 199.2, 153.1, 137.0, 136.1, 133.3, 128.8, 128.2, 117.6, 82.4, 34.1, 28.6, 28.0.

4.3.7. Carbonic acid 4-(*t*-butoxycarbonyl-hydrazono)-4-phenyl-1-vinyl-butyl ester *t*-butyl ester (6). To a solution of the crude ketone **18** (370 mg, 1.3 mmol) in hexane (2 mL) was added *t*-butyl carbazate (250 mg, 1.9 mmol). After refluxing overnight, the solution was cooled to room temperature. Concentration of the solvent in vacuo and purification by chromatography (10:1 hexanes/EtOAc) gave three fractions of material: the desired (*E*)-hydrazone **6** (239 mg, 46%), a mixture of (*E*) and (*Z*) isomers (224 mg, 43%), and the undesired (*Z*)-isomer (50 mg, 10%), all as thick colorless liquids. Charaterization of the (*E*)-isomer. IR (film) 3238, 2980, 2933, 1742, 1528, 1494, 1368, 1273, 1252, 1163 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.85 (br s, 1H), 7.74 (m, 2H), 7.32 (m, 3H), 5.82 (ddd, $J=17.2$, 10.8, 6.4 Hz, 1H), 5.33 (d, $J=17.2$ Hz, 1H), 5.27 (d, $J=10.8$ Hz, 1H), 5.05 (q, $J=6.3$ Hz, 1H), 2.65 (t, $J=8.4$ Hz, 2H), 1.87 (m, 2H), 1.54 (s, 9H), 1.48 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.0, 153.0, 149.8, 137.0, 135.5, 129.4, 128.6, 126.4, 118.3, 82.8, 81.6, 77.0, 60.2, 28.5, 28.0, 21.7; HRMS (EI-MS) [M+] Calcd for $C_{22}H_{32}N_2O_2$ 404.2311, found 404.2294. Characterization of the minor (*Z*)-isomer. IR (film) 3366, 2979, 2933, 1744, 1714, 1483, 1368, 1275, 1255, 1161 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.56 (br s, 1H), 7.47 (t, $J=7.2$ Hz, 2H), 7.40 (t, $J=7.2$ Hz, 1H), 7.17 (d, $J=6.8$ Hz, 2H), 5.73 (ddd, $J=17.2$, 10.8, 6.8 Hz, 1H), 5.23 (d, $J=17.2$ Hz, 1H), 5.15 (d, $J=10.4$ Hz, 1H), 5.00 (q, $J=6.4$ Hz, 1H), 2.60 (m, 2H), 1.87 (q, $J=7.6$ Hz, 2H), 1.43 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.1, 152.8, 136.1, 133.8, 129.8, 129.6, 127.1, 117.5, 82.2, 81.3, 77.5, 34.2, 31.0, 28.4, 28.0.

4.3.8. *N′*-(3-Phenyl-propyl)-hydrazinecarboxylic acid *t*-butyl ester (3e). To a solution of *N′*-(3-phenyl-propyl-idene)-hydrazinecarboxylic acid *t*-butyl ester **2f** (267 mg, 1.1 mmol) in MeOH (5 mL) at 0 °C was added $NaCNBH_3$ (135 mg, 2.2 mmol), along with a few drops of AcOH to achieve a pH of 4–5. After 15 min, the ice bath was removed. Upon completion of the reaction (by TLC), saturated $NaHCO_3$ was added, and the aqueous layer was extracted with EtOAc. The combined EtOAc layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo to give a colorless oil. Purification by chromatography (hexanes/EtOAc, 4:1 → 2:1) gave alkyl hydrazide **3e** (114 mg, 46%). IR (film) 3316, 2977, 2934, 2863, 1711, 1454, 1367, 1284, 1234, 1155 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.27 (m, 2H), 7.17 (m, 3H), 6.01 (br s, 1H), 3.95 (br s, 1H), 2.87 (t, $J=8.7$ Hz, 2H), 2.67 (t, $J=7.8$ Hz, 2H), 1.76 (m, 2H), 1.46 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.0, 142.2, 128.6, 128.6, 126.0, 80.7, 51.7, 33.5, 29.7, 28.6; HRMS (EI-MS) [$M^+ - i$-C_4H_8] Calcd for $C_{10}H_{14}N_2O_2$ 194.1055, found 194.1052.

4.4. Representative procedure for allylic amination

To a solution of hydrazone **2a** (70 mg, 0.30 mmol) and allylic carbonate **1a** (40 mg, 0.20 mmol) in dry THF (0.2 mL) under argon was added Et_2Zn (1.0 M in hexanes, 0.15 mL, 0.15 mmol). The resulting solution was allowed to stir at 25 °C for 8 h to ensure complete consumption of Et_2Zn. After this time, NH_4I (29 mg, 0.20 mmol) was added, followed by a solution of [Ir(COD)Cl_2] (6.7 mg, 5 mol%) and pyridine (1.6 μL, 10 mol%) in THF (0.2 mL). After the reaction was deemed complete by TLC (typically less than 30 min), the reaction mixture was concentrated in vacuo and the resulting residue was purified by flash column chromatography to give the desired allylic amination product **4a** (56 mg, 89%) as a clear, colorless oil.

4.4.1. *N′*-(1-Phenyl-ethylidene)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4a). IR (film) 2960, 2930, 1690, 1370, 1300, 1160 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.81 (m, 2H), 7.39 (m, 3H), 6.04 (br m, 1H), 5.22 (d, $J=17.4$ Hz, 1H), 5.13 (dq, $J=10.2$, 0.9 Hz, 1H), 4.68 (br m, 1H), 2.22 (s, 3H), 1.30–1.74 (m, 4H), 1.46 (s, 9H), 0.92 (t, $J=7.4$ Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 152.4, 138.4, 138.1, 130.3, 128.5, 127.2, 116.5, 80.8, 62.5, 34.9, 28.7, 19.7, 17.3, 14.2; HRMS (DCI-MS) [M+] Calcd for $C_{19}H_{29}N_2O_2$ 317.2229, found 317.2221.

4.4.2. *N′*-(1-Phenyl-ethylidene)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid benzyl ester (4b). Following the representative procedure, the reaction of hydrazone **2b** (80 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4b** (60 mg, 86%) as a clear, colorless oil. IR (film) 3066, 3033, 2958, 2872, 1703, 1283 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.85 (d, $J=7.0$ Hz, 2H), 7.43 (m, 3H), 7.36 (m, 5H), 6.05 (br m, 1H), 5.21 (m, 4H), 4.80 (br m, 1H), 2.20 (s, 3H), 1.76 (m, 1H), 1.62 (m, 1H), 1.36 (m, 2H), 0.93 (t, $J=7.0$ Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 171.5, 153.1, 138.0, 137.6, 136.7, 130.6, 128.8, 128.6, 128.3, 127.2, 116.9, 67.6, 62.2, 34.7, 19.7, 17.3, 14.2; HRMS (DCI-MS) [M+] Calcd for $C_{22}H_{27}N_2O_2$ 351.2072, found 351.2074.

4.4.3. *N′*-(1-Phenyl-ethylidene)-*N*-(1-vinyl-butyl)-*N*-*p*-toluenesulfonylhydrazine (4c). Following the representative procedure, the reaction of hydrazone **2c** (86 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4c** (68 mg, 92%) as a clear, colorless oil. IR (film) 3069, 3028, 2959, 2931, 2872, 1959, 1351, 1296, 1163, 1089 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.93 (d, $J=7.0$ Hz, 2H), 7.67 (d, $J=7.0$ Hz, 2H), 7.52 (t, $J=7.5$ Hz, 1H), 7.47 (t, $J=7.5$ Hz, 2H), 7.27 (d, $J=8.0$ Hz, 2H), 5.68 (ddd, $J=18.5$, 10.5, 7.5 Hz, 1H), 4.93 (d, $J=17.5$ Hz, 1H), 4.83 (d, $J=10.5$ Hz, 1H), 4.43 (m, 1H), 2.66 (s, 3H), 2.45 (s, 3H), 1.33 (m, 4H), 0.88 (t, $J=7.0$ Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 178.8, 143.7, 137.6, 135.5, 135.1, 131.3, 129.3, 129.2, 128.7, 127.6, 117.2, 65.0, 35.6, 21.9, 19.6, 18.3, 14.0; HRMS (EI-MS) [M+] Calcd for $C_{21}H_{26}N_2O_2S$ 370.1715, found 370.1707.

4.4.4. Acetic acid *N′*-(1-phenyl-ethylidene)-*N*-(1-vinyl-

butyl)-hydrazide (4d). Following the representative procedure, the reaction of hydrazone **2d** (53 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave of **4d** (9 mg, 17%) as a clear, colorless oil. IR (film) 3072, 2959, 2931, 2872, 1651, 1446, 1379, 1301 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.20–7.40 (m, 5H), 5.82 (m, 1H), 5.27 (d, $J=18.0$ Hz, 1H), 5.16 (d, $J=10.5$ Hz, 1H), 4.40 (br m, 1H), 2.33 (s, 3H), 1.88 (s, 3H), 1.81 (m, 1H), 1.63 (m, 1H), 1.40 (m, 2H), 0.96 (t, $J=7.5$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.8, 136.6, 131.5, 128.8, 128.4, 127.3, 117.9, 59.7, 33.8, 21.9, 19.7, 17.2, 14.1; HRMS (EI-MS) [M+] Calcd for $C_{16}H_{22}N_2O$ 258.17321, found 258.1719.

4.4.5. N'-Benzylidene-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4e). Following the representative procedure, the reaction of hydrazone **2e** (66 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4e** (53 mg, 88%) as a clear, colorless oil. IR (film) 3078, 2961, 2933, 2873, 1699, 1368, 1292, 1156 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 8.90 (br s, 1H), 7.71 (d, $J=7.5$ Hz, 2H), 7.39 (m, 3H), 6.06 (ddd, $J=17.5$, 10.5, 7.0, 1H), 5.19 (d, $J=17.0$ Hz, 1H), 4.82 (q, $J=7.0$ Hz, 1H), 1.94 (m, 1H), 1.67 (m, 1H), 1.56 (s, 9H), 1.37 (m, 2H), 0.96 (t, $J=7.5$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.4, 151.6, 138.6, 136.1, 129.8, 128.7, 127.4, 115.8, 81.5, 62.8, 35.0, 28.6, 18.2, 14.0; HRMS (FAB-MS) [M+] Calcd for $C_{18}H_{26}N_2O_2$ 302.1994, found 302.2007.

4.4.6. N'-(3-Phenyl-propylidene)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4f). Following the representative procedure, the reaction of hydrazone **2f** (74 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4f** (54 mg, 82%) as a clear, colorless oil. IR (film) 3064, 3027, 2960, 2932, 2873, 1697, 1454, 1367, 1294, 1162 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.96 (t, $J=5.1$ Hz, 1H), 7.28 (m, 2H), 7.20 (m, 3H), 5.88 (ddd, $J=16.8$, 11.1, 6.9 Hz, 1H), 5.09 (d, $J=17.1$ Hz, 1H), 5.08 (d, $J=11.1$ Hz, 1H), 4.59 (dt, $J=8.7$, 6.8 Hz, 1H), 2.88 (t, $J=7.6$ Hz, 2H), 2.67 (m, 2H), 1.66 (m, 1H), 1.48 (m, 1H), 1.47 (s, 9H), 1.25 (sextet, $J=7.4$ Hz, 2H), 0.88 (t, $J=7.4$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 160.8, 153.9, 141.3, 138.3, 128.6, 126.2, 115.8, 81.0, 60.8, 35.2, 34.5, 32.5, 28.6, 19.5, 14.0; HRMS (EI-MS) [M+] Calcd for $C_{20}H_{30}N_2O_2$ 330.2307, found 330.2294.

4.4.7. N'-(1-Ethyl-propylidene)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4g). Following the representative procedure, the reaction of hydrazone **2g** (60 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4g** (49 mg, 86%) as a clear, colorless oil. IR (film) 3077, 2974, 2936, 2875, 1698, 1636, 1460, 1367, 1302, 1253, 1166 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 5.87 (br m, 1H), 5.15 (d, $J=17.4$ Hz, 1H), 5.09 (d, $J=10.2$ Hz, 1H), 4.53 (m, 1H), 2.39 (q, $J=7.5$ Hz, 2H), 2.24 (m, 2H), 1.20–1.60 (m, 4H), 1.43 (s, 9H), 1.34 (t, $J=7.5$ Hz, 3H), 1.02 (t, $J=7.5$ Hz, 3H), 0.90 (t, $J=7.5$ Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$; imine carbonyl not observed due to quadrupolar broadening): δ 152.9, 137.8, 116.6, 80.3, 61.1, 34.4, 28.6, 28.5, 25.0, 24.1, 19.7, 14.1, 11.5, 10.4; HRMS (EI-MS) [M+] Calcd for $C_{16}H_{30}N_2O_2$ 282.2307, found 282.2295.

4.4.8. N'-(1-Ethyl-propylidene)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid benzyl ester (4h). Following the representative procedure, the reaction of hydrazone **2h** (60 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4h** (61 mg, 75%) as a clear, colorless oil. IR (film) 3068, 3033, 2961, 2936, 2874, 1702, 1287 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.30 (m, 5H), 5.86 (br m, 1H), 5.15 (d, $J=17.6$ Hz, 1H), 5.09 (m, 3H), 4.60 (m, 1H), 2.36 (q, $J=7.6$ Hz, 2H), 2.19 (m, 2H), 1.60 (m, 1H), 1.51 (m, 1H), 1.26 (sextet, $J=7.2$ Hz, 2H), 1.08 (t, $J=7.6$ Hz, 3H), 0.94 (t, $J=7.6$ Hz, 3H), 0.87 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 183.2, 153.5, 137.4, 136.8, 128.6, 128.3, 128.2, 117.0, 67.4, 61.4, 34.4, 28.5, 24.4, 19.6, 14.1, 11.3, 10.3; HRMS (EI-MS) [M+] Calcd for $C_{19}H_{28}N_2O_2$ 316.2151, found 316.2144.

4.4.9. N'-[1-(4-Bromo-phenyl)-ethylidene]-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4i). Following the representative procedure, the reaction of hydrazone **2i** (94 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4i** (32 mg, 41%) as a clear, colorless oil. IR (film) 2961, 2931, 2873, 1699, 1304, 1158 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.73 (d, $J=8.5$ Hz, 2H), 7.53 (d, $J=8.5$ Hz, 2H), 6.04 (br m, 1H), 5.23 (d, $J=17.5$ Hz, 1H), 5.16 (d, $J=10.5$ Hz, 1H), 4.69 (br m, 1H), 2.21 (s, 3H), 1.72 (m, 1H), 1.59 (m, 1H), 1.49 (s, 9H), 1.35 (m, 2H), 0.94 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 168.8, 152.2, 138.0, 137.2, 131.7, 128.7, 124.8, 116.5, 81.0, 62.2, 34.9, 28.6, 19.7, 17.1, 14.2; HRMS (EI-MS) [M+] Calcd for $C_{19}H_{27}N_2O_2Br$ 394.1255, found 394.1260.

4.4.10. N'-Pent-4-ynylidene-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (4j). Following the representative procedure, the reaction of hydrazone **2j** (42 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **4j** (40 mg, 71%) as a clear, colorless oil. IR (film) 3313, 2961, 2933, 2873, 1697, 1368, 1293, 1161 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 8.03 (t, $J=4.4$ Hz, 1H), 5.90 (ddd, $J=17.2$, 10.4, 6.8 Hz, 1H), 5.08 (m, 2H), 4.60 (m, 1H), 2.53 (m, 2H), 2.42 (m, 2H), 1.94 (t, $J=2.8$ Hz, 1H), 1.74 (m, 1H), 1.52 (m, 1H), 1.45 (s, 9H), 1.26 (sextet, $J=7.4$ Hz, 2H), 0.88 (t, $J=7.4$ Hz); ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.6, 153.7, 138.3, 115.8, 83.6, 81.2, 69.0, 61.0, 34.6, 62.7, 28.6, 19.4, 15.7, 14.0; HRMS (DCI-MS) [M+] Calcd for $C_{16}H_{26}N_2O_2$ 278.1994, found 278.1998.

4.4.11. *N*-(1-Phenyl-allyl)-N'-(1-phenyl-ethylidene)-hydrazinecarboxylic acid *t*-butyl ester (4k). Following the representative procedure, the reaction of hydrazone **2a** (70 mg, 0.30 mmol) with allylic carbonate **1b** (47 mg, 0.20 mmol) gave **4k** (63 mg, 90%) as a clear, colorless oil. IR (film) 3062, 2976, 2929, 1696, 1366, 1300, 1163 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, $J=6.4$ Hz, 2H), 7.44 (d, $J=7.6$ Hz, 2H), 7.33 (m, 5H), 7.22 (t, $J=7.6$ Hz, 1H), 6.34 (ddd, $J=17.6$, 9.6, 7.2 Hz, 1H), 5.89 (d, $J=6.8$ Hz, 1H), 5.29 (d, $J=16.8$ Hz, 1H), 5.28 (d, $J=10.8$ Hz, 1H), 2.14 (s, 3H), 1.42 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.2, 152.2, 140.4, 138.2, 136.5, 130.3, 128.4, 128.2, 128.4, 127.4, 127.2, 118.0, 81.1, 65.7, 28.6, 17.4; HRMS (DCI-MS) [M+] Calcd for $C_{22}H_{27}N_2O_2$ 351.2072, found 351.2069.

4.4.12. *N*-(1-Phenethyl-allyl)-*N′*-(1-phenyl-ethylidene)-hydrazinecarboxylic acid *t*-butyl ester (4l). Following the representative procedure, the reaction of hydrazone **2a** (70 mg, 0.30 mmol) with allylic carbonate **1c** (52 mg, 0.20 mmol) gave **4l** (63 mg, 83%) as a clear, colorless oil. IR (film) 3026, 2976, 2930, 1700, 1366, 1302, 1162 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.83 (m, 2H), 7.40 (m, 3H), 7.26 (m, 2H), 7.18 (m, 3H), 6.09 (br m, 1H), 5.23 (d, J=17.1 Hz, 1H), 5.17 (d, J=11.1 Hz, 1H), 4.70 (m, 1H), 2.63 (t, J=7.8 Hz, 2H), 2.26 (s, 3H), 2.06 (m, 1H), 1.91 (m, 1H), 1.45 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.3, 152.4, 142.2, 138.3, 137.8, 130.4, 128.8, 128.6, 128.5, 127.2, 126.1, 116.9, 81.0, 61.9, 34.8, 32.9, 28.6, 17.4; HRMS (EI-MS) [M+] Calcd for $C_{24}H_{30}N_2O_2$ 378.2307, found 378.2288.

4.4.13. *N′*-(1-Vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (5a). Following the representative procedure, the reaction of hydrazine **3a** (40 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **5a** (40 mg, 93%) as a clear, colorless oil. IR (film) 3320, 2960, 1720, 1460, 1370, 1280, 1250, 1170 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 6.10 (br s, 1H), 5.55 (ddd, J=8.4, 10.0, 6.8 Hz, 1H), 5.12 (d, J=17.2 Hz, 1H), 5.11 (d, J=10.4 Hz, 1H), 3.89 (br s, 1H), 3.34 (br m, 1H), 1.41 (s, 9H), 1.2–1.4 (m, 4H), 0.87 (t, J=7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.9, 139.4, 117.9, 80.5, 63.8, 35.3, 28.6, 19.1, 14.3; HRMS (DCI-MS) [M+] Calcd for $C_{11}H_{23}N_2O_2$ 215.1760, found 215.1759.

4.4.14. *N′*-(1-Vinyl-butyl)-hydrazinecarboxylic acid benzyl ester (5b). Following the representative procedure, the reaction of hydrazine **3b** (50 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **5b** (43 mg, 86%) as a clear oil. IR (film) 3320, 3070, 3030, 2960, 2930, 2870, 1720, 1460, 1260 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.35 (m, 5H), 6.21 (br s, 1H), 5.58 (dt, J=17.7, 9.0 Hz, 1H), 5.15 (m, 4H), 3.96 (br s, 1H), 3.39 (br s, 1H), 1.47 (m, 1H), 1.33 (m, 3H), 0.90 (t, J=6.6 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 157.4, 139.1, 136.4, 128.8, 128.5, 128.4, 118.3, 67.3, 63.9, 35.2, 19.1, 14.3; HRMS (DCI-MS) [M+] Calcd for $C_{14}H_{21}N_2O_2$ 249.1603, found 249.1596.

4.4.15. *N′*-(1-Vinyl-butyl)-*N*-*p*-toluenesulfonyl hydrazine (5c). Following the representative procedure, the reaction of hydrazine **3c** (56 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **5c** (31 mg, 57%) as a clear, colorless oil. IR (film) 3230, 2950, 2930, 2870, 1320, 1160 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.83 (d, J=8.5 Hz, 2H), 7.33 (d, J=9.0 Hz, 2H), 6.01 (br s, 1H), 5.37 (dt, J=17.0, 10.0 Hz, 1H), 5.20 (dd, J=10.5, 1.5 Hz, 1H), 5.02 (d, J=17.0 Hz, 1H), 3.80 (br s, 1H), 2.87 (q, J=8.5 Hz, 1H), 2.45 (s, 3H), 1.36 (m, 1H), 1.22 (m, 3H), 0.80 (t, J=7.0 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 144.3, 137.5, 135.9, 129.8, 128.5, 119.5, 63.6, 34.9, 21.8, 19.0, 14.0; HRMS (DCI-MS) [M+] Calcd for $C_{13}H_{21}N_2O_2S$ 269.1323, found 169.1334.

4.4.16. *N′*-(1-Phenyl-allyl)-hydrazinecarboxylic acid *t*-butyl ester (5e). Following the representative procedure, the reaction of hydrazine **3a** (40 mg, 0.30 mmol) with allylic carbonate **1b** (47 mg, 0.20 mmol) gave **5e** (44 mg, 88%) as a clear oil. IR (film) 3315, 2978, 1715, 1454, 1367, 1277, 1253, 1162 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.25–7.35 (m, 5H), 6.00 (br s, 1H), 5.92 (ddd, J=17.6, 10.4, 7.6 Hz, 1H), 5.27 (d, J=17.2 Hz, 1H), 5.16 (d, J=10.0 Hz, 1H), 4.62 (br d, J=6.4 Hz, 1H), 4.21 (br s, 1H), 1.42 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.8, 140.7, 138.5, 128.8, 128.1, 127.9, 117.5, 80.7, 67.4, 28.6; HRMS (DCI-MS) [M+] Calcd for $C_{14}H_{21}N_2O_2$ 249.1603, found 249.1612.

4.4.17. *N′*-(1,1-Dimethyl-allyl)-hydrazinecarboxylic acid *t*-butyl ester (5f). Following the representative procedure, the reaction of hydrazine **3a** (40 mg, 0.30 mmol) with allylic carbonate **1d** (37 mg, 0.20 mmol) gave **5f** (33 mg, 82%) as a sticky colorless oil. IR (film) 3270, 3225, 2980, 2930, 1710, 1455, 1365, 1280, 1255, 1165 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 5.91 (br s, 1H), 5.80 (dd, J=17.0, 10.5 Hz, 1H), 5.10 (d, J=17.0 Hz, 1H), 5.09 (d, J=10.5 Hz, 1H), 3.82 (br s, 1H), 1.46 (s, 9H), 1.17 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 157.2, 144.0, 113.7, 80.4, 58.6, 28.6, 24.8; HRMS (DCI-MS) [M+] Calcd for $C_{10}H_{21}N_2O_2$ 201.1603, found 201.1599.

4.4.18. *N′*-(3-Phenyl-propyl)-*N′*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (5g). Following the representative procedure, the reaction of hydrazine **3e** (52 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **5g** (44 mg, 86%) as a clear, colorless oil. IR (film) 3234, 3064, 3026, 2959, 2931, 2871, 1743, 1695, 1392, 1633, 1171 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.10–7.30 (m, 5H), 5.56 (ddd, J=17.4, 10.5, 9.0 Hz, 1H), 5.22 (dd, J=10.2, 2.0 Hz, 1H), 5.10 (dd, J=17.1, 1.8 Hz, 1H), 4.90 (br s, 1H), 3.08 (br m, 1H), 2.72 (br m, 3H), 2.53 (br m, 1H), 1.78 (m, 2H), 1.64 (m, 1H), 1.46 (m, 1H), 1.46 (s, 9H), 1.38 (m, 2H), 0.90 (t, J=6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.6, 142.7, 136.1, 128.8, 128.4, 125.8, 118.9, 79.6, 69.0, 54.5, 34.3, 33.4, 29.2, 28.6, 19.6, 14.3; HRMS (EI-MS) [M+] Calcd for $C_{20}H_{32}N_2O_2$ 332.2463, found 332.2467.

4.4.19. *N′*-Isopropyl-*N′*-(1-vinyl-butyl)-hydrazinecarboxylic acid *t*-butyl ester (5i). Following the representative procedure, the reaction of hydrazine **3f**[32] (75 mg, 0.30 mmol) with allylic carbonate **1a** (40 mg, 0.20 mmol) gave **5g** (56 mg, 85%) as a colorless, viscous oil. Characterized as a mixture of rotamers. IR (film) 3236, 3126, 3075, 2968, 2933, 2873, 1750, 1695, 1392, 1365, 1174 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 5.68 (m, 1H), 5.10 (m, 3H), 2.8–8.2 (br m, 2H), 1.55 (m, 1H), 1.41 (s, 9H), 1.41 (m, 1H), 1.33 (m, 2H), 1.00 (d, J=6.3 Hz, 6H), 0.84 (t, J=7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.2, 156.3, 139.0, 137.3, 135.8, 118.3, 117.7, 116.7, 79.9, 79.4, 68.1, 66.2, 64.1, 54.4, 52.7, 51.2, 34.6, 34.3, 28.5, 28.0, 21.3, 19.4, 14.3; HRMS (EI-MS) [M+] Calcd for $C_{14}H_{28}N_2O_2$ 256.2150, found 256.2138.

4.4.20. 3-Phenyl-6-vinyl-5,6-dihydro-4H-pyridazine-1-carboxylic acid *t*-butyl ester (7). Following the representative procedure, the reaction of hydrazine **6** (40 mg, 0.10 mmol) gave **7** (25 mg, 88%) as a clear, colorless oil. IR (film) 3083, 3062, 2978, 2933, 1727, 1698, 1397, 1333, 1153 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.77 (d, 8.2 Hz, 2H), 7.32 (m, 3H), 5.72 (ddd, J=16.9, 10.5, 4.0 Hz, 1H), 5.14 (d, J=10.5 Hz, 1H), 5.01 (d, J=16.3 Hz, 1H), 4.99 (br m, 1H), 2.62 (d, J=17.7, 5.1 Hz, 1H), 2.38 (ddd, J=17.9, 12.9, 6.9 Hz, 1H), 1.99 (m, 2H), 1.54 (s, 9H); ^{13}C NMR

(125 MHz, $CDCl_3$): δ 153.4, 146.0, 138.0, 135.2, 129.0, 128.5, 125.5, 115.9, 81.5, 51.9, 28.5, 21.8, 18.9; HRMS (EI-MS) [M+] Calcd for $C_{17}H_{22}N_2O_2$ 286.1681, found 286.1668.

4.4.21. *N*-(1-Vinyl-butyl)-hydrazinecarboxylic acid benzyl ester (10). To a solution of hydrazone **4b** (35 mg, 0.10 mmol) in EtOH (2 mL) was added 37% HCl dropwise (0.5 mL). After 10 min, the reaction mixture was diluted with H_2O and washed with EtOAc. The aqueous layer was then brought to a basic pH (ca. 14) with NaOH and extracted with EtOAc. The combined EtOAc layers were then dried over Na_2SO_4 and concentrated in vacuo to give a crude residue. Purification by chromatography (hexanes/EtOAc, 4:1) gave hydrazine **10** (17.4 mg, 68%) as a clear, colorless oil. IR (film) 3341, 3223, 6038, 3034, 2958, 2933, 2873, 1699, 1404, 1298, 1096 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.33 (m, 5H), 5.83 (ddd, J=16.8, 10.8, 6.4 Hz, 1H), 5.15 (s, 2H), 5.09 (d, J=10.4 Hz, 1H), 5.08 (d, J=18.4 Hz, 1H), 4.52 (br m, 1H), 3.71 (br s, 2H), 1.73 (m, 1H), 1.48 (m, 1H), 1.24 (sextet, J=7.4 Hz, 2H), 0.88 (t, J=7.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.2, 137.4, 136.7, 128.7, 128.4, 128.2, 116.1, 67.9, 59.5, 33.6, 19.6, 14.0; HRMS (EI-MS) [M+] Calcd for $C_{14}H_{20}N_2O_2$ 248.1524, found 248.1516.

4.4.22. *N′*-(1-Phenyl-ethyl)-*N*-(1-vinyl-butyl)-hydrazinecarboxylic acid benzyl ester (11). To a solution of hydrazone **4b** (70 mg, 0.2 mmol) in MeOH (0.5 mL) at 0 °C was added $NaCNBH_3$ (25 mg, 0.4 mmol), along with a few drops of AcOH to achieve a pH of 4–5. After 15 min, the ice bath was removed. Upon completion of the reaction (by TLC), saturated $NaHCO_3$ was added, and the aqueous layer was extracted with EtOAc. The combined EtOAc layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo to give a colorless oil. Purification by chromatography (hexanes/EtOAc, 10:1) gave alkyl hydrazide **11** (64 mg, 90%) as a clear, sticky oil, which was characterized as a 1:1 mixture of diastereomers. IR (film) 3291, 3065, 3032, 2959, 2931, 2872, 1699, 1454, 1390, 1292, 1095, 670 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 7.30 (m, 10H), 5.85 (m, 1H), 5.46 (m, 1H), 5.17 (s, 4H), 4.90 (m, 4H), 4.20 (m, 4H), 1.55 (m, 2H), 1.32 (m, 8H), 1.11 (m, 4H), 0.80 (t, J=7.2 Hz, 3H), 0.69 (t, J=7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.3, 144.3, 144.0, 138.2, 137.9, 136.6, 128.8, 128.5, 128.4, 128.3, 128.0, 128.0, 127.6, 116.2, 116.0, 67.8, 67.8, 64.1, 63.1, 59.6, 34.6, 21.8, 21.5, 19.8, 19.7, 14.1, 14.0; HRMS (EI-MS) [M+] Calcd for $C_{22}H_{28}N_2O_2$ 352.2150, found 352.2140.

4.4.23. *N*-(1-Ethyl-butyl)-*N′*-(1-ethyl-propyl)-hydrazinecarboxylic acid *t*-butyl ester (12). Pd/C (ca. 7 mg) was added to a solution of the hydrazone **4g** (35 mg, 0.12 mmol) in EtOH (1 mL), and the reaction mixture was put under a balloon of hydrogen. After 8 h, the reaction was complete on TLC, and the reaction mixture was then filtered through celite. Concentration of the filtrate in vacuo gave dialkyl hydrazine **12** (31 mg, 89%) as a clear colorless oil. IR (film) 2969, 2934, 2875, 1693, 1460, 1366, 1329, 1178, 1152, 1104 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 4.20 (br s, 1H), 2.40 (q, J=7.3 Hz, 2H), 2.27 (br m, 2H), 1.45 (s, 9H), 1.2–1.8 (m, 8H), 1.15 (t, J=7.5 Hz, 3H), 1.06 (t, J=7.6 Hz, 3H), 0.91 (m, 6H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 153.3, 79.8, 59.8, 35.2, 28.6, 28.4, 26.1, 24.1, 20.0, 14.3, 11.5, 10.4; HRMS (EI-MS) [M+] Calcd for $C_{16}H_{34}N_2O_2$ 286.2620, found 286.2633.

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