

# Ruthenium Carbene-Mediated Construction of Strained Allenes via the Enyne Cross-Metathesis/Cyclopropanation of 1,6-Enynes

Ming Gao, Qiangqiang Gao, Xiangbin Hao, Ying Wu, Qingmin Zhang, Guohua Liu, and Rui Liu\*

Cite This: https://dx.doi.org/10.1021/acs.orglett.9b04662

idene undergoes a site-selective metathesis process to provide allenyl ruthenium carbene, which can be intramolecularly trapped



R1 = H, alkyl, aryl; R2 = alkyl



by the pendent C=C bond of enyne through a [2 + 2] cycloaddition/metal elimination process.

nyne metathesis, as an efficient strategy for C-C bond-E forming reactions, has the tremendous ability to construct complex molecules containing the 1,3-diene motif.<sup>1</sup> Among those extensively studied metathesis processes, the intermolecular enyne cross-metathesis are especially attractive, since this simplest cross-coupling or dimerization of two enyne molecules is able to produce many interesting molecules<sup>2</sup> with inherent selectivity and an atom-economical manner through those in-situ-generated metal carbenes. However, its application for the creation of allene structures has not been recognized yet, mainly because of the high activity of free unsaturated carbenes that often lead to complicated byproducts arising from uncontrollable polymerization induced by consecutive metathesis<sup>3</sup> or cyclopropanation processes.<sup>4</sup> Through investigations of the mechanism of enyne metathesis, we find that the key point for the formation of allenes mainly lies in the formation of in-situ-generated ruthenium vinylidene and its site-selective metathesis process of ruthenium vinylidene with the alkyne group of second enynes via the so-called "yne-then-ene" mechanism (Scheme 1B), rather than the "enethen-yne" mechanism (Scheme 1A<sub>3</sub>).<sup>5</sup>

A brief survey of the published literature found that homobimetallic ruthenium vinylidene can be activated by the addition of phenyl acetylene in the ring-closing metathesis reactions of 1,6-dienes, where Delaude proposed an intermediate transformation from ruthenium vinylidene to allenyl ruthenium carbene via a common [2 + 2] cycloaddition process (Scheme  $1A_1$ ).<sup>6</sup> Their speculation offered valuable information for the construction of allenes through the efficient capture of this allenyl ruthenium carbene intermediate. From a literature review of the reported methods used to capture ruthenium carbenes, it was found that there are numerous functional groups, for instance, amine,<sup>7</sup> aldehyde,<sup>8</sup> acetal,<sup>9</sup> that have the ability to trap ruthenium carbene. In particular, the trapping of ruthenium carbene with an alkene chain via a [2 + 2] cycloaddition/metal reductive elimination process generally produces cyclopropane-containing products.<sup>10</sup> Several interesting examples were presented by Iwasa et al., who used the ruthenium phenyloxazoline complex as a catalyst in the coupling reaction of diazoester and alkene/allene to produce cyclopropyl ester/ketone.<sup>11</sup> In the typical examples reported by Dixneuf, an intramolecular alkene side chain of enynes was utilized as a capture partner to successfully realize a cyclopropanation process to access alkenyl bicyclo[3.1.0]hexane (Scheme  $1A_2$ ).<sup>12</sup> In another report made by the Trost group, a similar strategy was performed to efficiently capture ruthenium carbene intermediates to create bicyclo[3.1.0]hexane.13

[ruthenium vinylidene]

Inspired by the above in-situ-generated allenic ruthenium carbene, together with the extensively studied intramolecular capture of ruthenium carbene, a ruthenium vinylidene-directed metathesis/cyclopropanation reaction pathway was designed for constructing strained allene, as shown in Scheme 1B. As we envisioned, the site-selective metathesis of in-situ-generated ruthenium vinylidene complex (A) and 1,6-enynes generates the allenyl ruthenium carbene intermediate (B), which can be intramolecularly captured by alkene motif, thereby realizing the construction of unprecedented bicyclo[3.1.0]hexyl allenes. This study not only represents a new methodology for the allenes synthesis to enrich allene chemistry, but also provides an example for the "yne-then-ene" mechanism of the metathesis process between ruthenium vinylidene and enyne.

In the proof-of-concept experiments, we have focused on cross-coupling reactions to test the feasibility of the ruthenium carbene-directed construction of allenes, as shown in Scheme 2. The stoichiometric tert-butyl ruthenium vinylidene

Received: December 28, 2019



Scheme 1. (A) Reported Transformation of Ruthenium Intermediates and Intramolecularly Capture of Ruthenium Carbene. (B) Ruthenium-Vinylidene-Directed Construction of Allenes via Enyne Metathesis/Cyclopropanation Pathway

#### A. Reported works





Scheme 2. Evaluation of Ruthenium Carbene-Directed Construction of Allenes



Me<sub>3</sub>CC=C=RuCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub>  $(1')^{14}$  steadily reacted with the 1,6-envne 1a at 25 °C to afford the cross-coupling product 2a (CCDC No. 1890919) in 69% isolated yield, where 11% of self-coupling product 3a was observed. Changing the N-linked 1,6-enyne 1a to the C-linked 1,6-enyne 1b yielded similar results, since the reaction also produced the cross-coupling product 2b and self-coupling product 3b. To our surprise, the yields of the self-coupling products sharply increased as the reaction temperature increased to 60 °C, indicating that the self-coupling process of 1,6-envne might be preferentially favored. Importantly, the formation of bicyclo[3.1.0]hexyl allene strongly suggests that the initial step comes from the metathesis of ruthenium vinylidene and alkyne groups of 1,6enyne through the "yne-then-ene" mechanism rather than "ene-then-yne" mechanism that often leads to 1,3-dienecontaining compounds.<sup>54</sup>

According to these interesting findings, we directly used the single 1a as the substrate and 10 mol %  $RuCl_2(PPh_3)_3$  as the catalyst in this reaction. The results showed that the reaction at

60 °C could steadily provide the clean self-coupling product (**3a**) with a 90% yield, even if in 1 g scale reaction (85%) (see the Supporting Information). By further screening the extensively used transition-metal complexes in the dimerization reaction of **1a**, we found that only isonomic metal (CpRu-(PPh<sub>3</sub>)<sub>2</sub>[PF<sub>6</sub>] or OsCl<sub>2</sub>(PPh<sub>3</sub>)<sub>3</sub>), as an electron-rich metal center, had the ability to construct **3a** with low to moderate yields (see the Supporting Information).

On the basis of our understanding of this dimerization process, a series of functionalized tosyl amide 1,6-enynes were further examined in this self-coupling construction of allenes, as shown in Table 1. Generally, this ruthenium-mediated

Table 1. Ruthenium-Mediated Dimerization of the Functionalized Tosyl Amide  $1^a$ 

0 R-S- 0	N RuCl <sub>2</sub> (PP CHC 1c-1n	h <sub>3</sub> ) <sub>3</sub> (10mol9 Cl <sub>3</sub> , 60 °C	%) 0 − − 0 0	-N -
entry	R	time (h)	yield <sup>b</sup> (%)	diasteromeric ratio, dr <sup>c</sup>
1	4-FPh (3c)	24	85	2.1/1
2	$3,5-F_2Ph(3d)$	24	81	1.7/1
3	4-ClPh (3e)	24	79	1.7/1
4	4-BrPh (3f)	24	83	1.7/1
5	4-CF <sub>3</sub> Ph (3g)	17	75	1.6/1
6	4-NO <sub>2</sub> Ph (3h)	29	68	1.6/1
7	4-MeOPh (3i)	21	69	2.1/1
8	2,4,6-Me <sub>3</sub> Ph (3j)	19	93	2.9/1
9	2,4,6- <sup>i</sup> Pr <sub>3</sub> Ph (3k)	35	78	3.4/1
10	naphthenyl (31)	21	86	2.0/1
11	Me (3m)	20	85	2.1/1
12	<sup><i>i</i></sup> Pr (3n)	20	83	2.6/1

<sup>*a*</sup>Reaction conditions:  $RuCl_2(PPh_3)_3$  (0.04 mmol) and substrate (0.4 mmol) were dissolved into 1.0 mL of CHCl<sub>3</sub> and the mixture was stirred under the reflux conditions for 12–35 h. <sup>*b*</sup>Isolated yield. <sup>*c*</sup>Determined by crude <sup>1</sup>H NMR.

dimerization reaction steadily produced the corresponding allenes in good yields with reasonable diastereomeric ratios (dr), ranging from 1.6/1 to 3/1. No significant effects on the steric features and electronic properties of the R group were observed (Table 1, entries 1-9). In addition, substrates with alkyl and naphthenyl substituents in the R group were also efficiently converted to their corresponding dimers with high isolated yields (Table 1, entries 10-12).

Moreover, it was also noted that this synthetic protocol displayed a certain tolerance and selectivity to other substrates, which is mainly reflected in the two types of alkene chains of 1,6-envnes: terminal and internal alkene chains, as shown in Scheme 3. In the case of 1,6-enynes with terminal alkenes, although the tosyl amide substrates were equipped with phenyl or benzyl group on the terminal alkenes, satisfactory yields were observed in the synthesis of 30 and 3p. Gratifyingly, the C-linked 1,6-enynes were also converted to their corresponding dimers (3b, 3q-3s) in high yields, albeit with longer reaction times. In the case of 1,6-enynes with internal alkenes, we found that the reactions with (Z)-configuration substrates could smoothly provide the self-coupling allenes 3t-3w in high yields, whereas those corresponding with the (E)configuration substrates only gave a complicated mixture without any desirable allenes. This observation suggests

# Scheme 3. Scope of Ruthenium-Mediated Dimerization Reactions<sup>*a*</sup>



"Reaction conditions:  $RuCl_2(PPh_3)_3$  (0.04 mmol) and substrate (0.4 mmol) were dissolved into 1.0 mL of CHCl<sub>3</sub> and the mixture was stirred under the reflux conditions for 14–40 h. Isolated yield. Determined by crude <sup>1</sup>H NMR.

substrate selectivity of 1,6-enynes loaded with internal alkenes, possibly because of a sensitive conformational demand of the trapped ruthenium carbene intermediate during the [2 + 2] cycloaddition step.

To gain mechanistic insight into the present dimerization of enyne, we then performed deuterium labeling and control experiments, mainly focusing on the formation of the ruthenium vinylidene step and the role of the alkene chain in 1,6-enynes. The cross-coupling reaction of 1' with 1a-dgave the deuterated product 2a-d while simultaneously maintaining the deuteration (97%) (see eq 1 in Scheme 4). The replacement of 1' with *tert*-butyl acetylene 4 and RuCl<sub>2</sub>(PPh<sub>3</sub>)<sub>3</sub> also provided the corresponding 2a-d in 42% yield, giving direct evidence that the proton at C-3 position of

# Scheme 4. Deuterium-Labeling and Control Experiments



**2a-d** is derived from the terminus of **4** (see eq 2 in Scheme 4), which was further confirmed by the self-coupling reaction of **1a-d**, where **3a-d**<sub>2</sub> was isolated in 79% yield (see eq 4 in Scheme 4). Interestingly, the presence of D<sub>2</sub>O as a cosolvent was able to install deuterium at the C-3 position of **2a-d**<sub>2</sub>, demonstrating that the H/D exchange process might be involved during the ruthenium vinylidene-forming process, possibly because of the formation of ruthenium hydride species (see eq 3 in Scheme 4). In order to explain the role of the alkene chain of 1,6-enynes, a cross-coupling reaction of **1a** with **5** was performed. However, only the corresponding dimer **3a** was observed and **5** was almost fully recovered. This finding demonstrates that the trapping of a carbene intermediate via a cyclopropanation step comes from an adjacent intramolecular alkene chain, rather than an intermolecular alkene molecule.

With our understanding of the self-coupling process and the obtained experimental results of the dimerization reactions (Table 1 and Scheme 4), a ruthenium-mediated catalytic mechanism featuring an enyne metathesis/cyclopropanation process is proposed, as shown in Scheme 5. In an initial step,

Scheme 5. Proposed Catalytic Mechanism



the ruthenium hydride species I generated from the reaction of  $RuCl_2(PPh_3)_3$  and the first 1a molecule gives a ruthenium vinylidene complex (II),<sup>15</sup> which was indirectly verified by the deuterium labeling experiments (see eqs 1-4 in Scheme 4). Then, cross-envne metathesis occurs between the ruthenium vinylidene complex (II) and the triple bond of the second 1a molecule in a tail-to-tail orientation, resulting in the formation of an allenyl ruthenium carbene intermediate (IV) through a ruthenacyclobutene intermediate (III) coming from a [2 + 2]cycloaddition-like step.<sup>6,16</sup> Finally, trapping IV with a pendant  $\dot{C}=C$  bond in the second 1a molecule transfers to intermediate (V) to encourage cyclopropanation, which releases 3a to finish the catalytic cycle.<sup>12</sup> In addition, an attempt to capture the carbon signal of the Ru=C- moiety in IV to confirm the previously proposed in situ transformation from II to V was unsuccessful, because of its high reactivity in the dimerization of 1a monitored by an in situ <sup>13</sup>C NMR spectra (see the Supporting Information); however, two new signals that appeared at 134.7 and 126.6 ppm might be

responsible for the formation of ruthenium vinylidene intermediate II.

In conclusion, we developed an unprecedented self-coupling method to construct bicyclo[3.1.0]hexyl allene derivatives, using the simple and commercially available  $RuCl_2(PPh_3)_3$  as a catalyst. Investigation of the alkene configurations of the envnes disclosed a sensitive conformational demand, where only 1,6-envnes with a terminal alkene or an internal (Z)configured alkene were favorable in the self-coupling construction of allenes. Our mechanistic investigation indicates that the in-situ-generated ruthenium vinylidene site-selectively reacts with the alkyne side of enyne in a tail-to-tail orientation, which results in allenyl ruthenium carbene that can be intramolecularly trapped by the pendent C=C double bond via a cyclopropanation step. This protocol also provides an example for the "yne-then-ene" mechanism of the metathesis process between ruthenium vinylidene and enyne via the formation of cyclopropyl allenes derivatives, rather than the traditional 1,3-diene-containing products.

## ASSOCIATED CONTENT

#### **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.9b04662.

Experimental details for the preparation of all substrates and catalytic reactions; screening of solvents and metal complexes (PDF)

### **Accession Codes**

CCDC 1890919 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data\_request/cif, or by emailing data\_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

#### AUTHOR INFORMATION

#### **Corresponding Author**

 Rui Liu – Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China; orcid.org/0000-0002-7916-3675; Email: rliu@shnu.edu.cn

#### Authors

- Ming Gao Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China
- Qiangqiang Gao Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China
- Xiangbin Hao Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China

- Ying Wu Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China
- Qingmin Zhang Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China
- Guohua Liu Joint Laboratory of International Cooperation of Resource Chemistry of Ministry of Education, Key Laboratory of Resource Chemistry of Ministry of Education, and Shanghai Key Laboratory of Rare Earth Functional Materials, Shanghai Normal University, Shanghai, China; orcid.org/0000-0001-8407-3095

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.orglett.9b04662

#### Notes

The authors declare no competing financial interest.

# ACKNOWLEDGMENTS

We are grateful to the National Natural Science Foundation of China (Nos. 21672149 and 21872095) for financial support.

# REFERENCES

(1) (a) Diver, S. T.; Giessert, A. J. Enyne metathesis (Enyne Bond Reorganization). *Chem. Rev.* 2004, 104, 1317–1382. (b) Kotha, S.; Meshram, M.; Tiwari, A. Advanced approach to polycyclics by a synergistic combination of enyne metathesis and Diels-Alder reaction. *Chem. Soc. Rev.* 2009, 38, 2065–2092. (c) Diver, S. T. Ruthenium vinyl carbene intermediates in enyne metathesis. *Coord. Chem. Rev.* 2007, 251, 671–701. (d) Hu, Y.; Bai, M.; Yang, Y.; Zhou, Q. Metal-catalyzed enyne cycloisomerization in natural product total synthesis. *Org. Chem. Front.* 2017, 4, 2256–2275. (e) Santamaría, J.; Aguilar, E. Beyond fischer and schrock carbenes: non-heteroatom-stabilized group 6 metal carbene complexes-a general overview. *Org. Chem. Front.* 2016, 3, 1561–1588. (f) Villar, H.; Frings, M.; Bolm, C. Ring closing enyne metathesis: A powerful tool for the synthesis of heterocycles. *Chem. Soc. Rev.* 2007, 36, 55–66.

(2) (a) Kim, M.; Miller, R. L.; Lee, D. Cross and ring-closing metathesis of 1,3-diynes: Metallotropic [1,3]-shift of ruthenium carbenes. J. Am. Chem. Soc. 2005, 127, 12818–12819. (b) Park, S.; Kim, M.; Lee, D. Tandem sequence of cross metathesis-ring-closing metathesis reaction of alkynyl silyloxy-tethered enynes. J. Am. Chem. Soc. 2005, 127, 9410–9415. (c) Yun, S. Y.; Wang, K.-P.; Kim, M.; Lee, D. Initiation and termination mode of enyne cross-metathesis and metallotropic [1,3]-shift controlled by remote substituents. J. Am. Chem. Soc. 2010, 132, 8840–8841.

(3) (a) Bielawski, C. W.; Grubbs, R. H. Highly efficient ring-opening metathesis polymerization (ROMP) using new ruthenium catalysts containing N-heterocyclic carbene ligands. *Angew. Chem., Int. Ed.* **2000**, *39*, 2903–2906. (b) Morontsev, A. A.; Gringolts, M. L.; Filatova, M. P.; Peregudov, A. S.; Akmalov, T. R.; Masoud, S. M.; Osipov, S. N.; Denisova, Y. I.; Kudryavtsev, Y. V. Ruthenium-carbene complexes in the synthesis of polybutadiene and its cross-metathesis with polynorbornene. *Polym. Sci., Ser. C* **2019**, *61*, 65–75. (c) Song, K.; Kim, K.; Hong, D.; Kim, J.; Heo, C. E.; Kim, H. I.; Hong, S. H. Highly active ruthenium metathesis catalysts enabling ring-opening metathesis polymerization of cyclopentadiene at low temperatures. *Nat. Commun.* **2019**, *10*, 3860.

(4) Nishiyama, H. Ruthenium-Catalyzed Cyclopropanation. In Ruthenium in Organic Synthesis; Murahashi, S. I., Ed.; Wiley-VCH

Verlag GmbH & Co. KGaA: Weinheim, Germany, 2004; pp 179–187.

(5) (a) Dolan, M. A.; Dixon, A. D. C.; Chisholm, J. D.; Clark, D. A. Ruthenium dihydride complexes as enyne metathesis catalysts. *Tetrahedron Lett.* **2018**, *59*, 4471–4474. (b) Galan, B. R.; Giessert, A. J.; Keister, J. B.; Diver, S. T. Studies on the mechanism of intermolecular enyne metathesis: kinetic method and alkyne substituent effects. J. Am. Chem. Soc. **2005**, *127*, 5762–5763. (c) Lippstreu, J. J.; Straub, B. F. Mechanism of enyne metathesis catalyzed by grubbs ruthenium-carbene complexes: A DFT study. J. Am. Chem. Soc. **2005**, *127*, 7444–7457.

(6) Borguet, Y.; Sauvage, X.; Zaragoza, G.; Demonceau, A.; Delaude, L. Synthesis and catalytic evaluation in olefin metathesis of a second-generation homobimetallic ruthenium-arene complex bearing a vinylidene ligand. *Organometallics* **2011**, *30*, 2730–2738.

(7) González-Rodríguez, C.; Suárez, J. R.; Varela, J. A.; Saá, C. Nucleophilic addition of amines to ruthenium carbenes: ortho-(alkynyloxy)benzylamine cyclizations towards 1,3-benzoxazines. *Angew. Chem., Int. Ed.* **2015**, *54*, 2724–2728.

(8) (a) Cambeiro, F.; López, S.; Varela, J. A.; Saá, C. Vinyl dihydropyrans and dihydrooxazines: cyclizations of catalytic ruthenium carbenes derived from alkynals and alkynones. *Angew. Chem., Int. Ed.* **2014**, *53*, 5959–5963. (b) Padín, D.; Cambeiro, F.; Fañanás-Mastral, M.; Varela, J. A.; Saá, C. [2 + 1] Cycloaddition of catalytic ruthenium vinyl carbenes: a stereoselective controlled access to (*Z*)- and (*E*)-vinyl epoxypyrrolidines. *ACS Catal.* **2017**, *7*, 992–996.

(9) Cambeiro, F.; Lopez, S.; Varela, J. A.; Saa, C. Cyclization by Catalytic Ruthenium Carbene Insertion into  $C_{sp3}$ -H Bonds. *Angew. Chem., Int. Ed.* **2012**, *51*, 723–727.

(10) (a) Demonceau, A.; Noels, A. F.; Saive, E.; Hubert, A. J. Ruthenium-catalysed ring-opening metathesis polymerization of cycloolefins initiated by diazoesters. J. Mol. Catal. 1992, 76, 123-132. (b) Demonceau, A.; Saive, E.; de Froidmont, Y.; Noels, A. F.; Hubert, A. J.; Chizhevsky, I. T.; Lobanova, I. A.; Bregadze, V. I. Olefin cyclopropanation reactions catalysed by novel ruthenacarborane clusters. Tetrahedron Lett. 1992, 33, 2009-2012. (c) Simal, F.; Demonceau, A.; Noels, A. F. Synthesis and evaluation of ruthenium catalysts containing diamine-based ligands in olefin cyclopropanation. Tetrahedron Lett. 1998, 39, 3493-3496. (d) Baratta, W.: Herrmann. W. A.; Kratzer, R. M.; Rigo, P. Half-sandwich ruthenium(II) catalysts for C-C coupling reactions between alkenes and diazo compounds. Organometallics 2000, 19, 3664-3669. (e) Leadbeater, N. E.; Scott, K. A.; Scott, L. J. Preparation of a resin-bound arene-ruthenium complex and assessment of its use in enol formate synthesis and olefin cyclopropanation. J. Org. Chem. 2000, 65, 3231-3232. (f) Werle, T.; Maas, G. Ruthenium-catalyzed diastereoselective syn-cyclopropanation of trisubstituted alkenes with diazoacetates. Adv. Synth. Catal. 2001, 343, 37-40. (g) Maas, G. Ruthenium-catalysed carbenoid cyclopropanation reactions with diazo compounds. Chem. Soc. Rev. 2004, 33, 183-190. (h) Nishiyama, H. Cyclopropanation with ruthenium catalysts. In Ruthenium Catalysts and Fine Chemistry, Bruneau, C., Dixneuf, P. H., Eds.; Springer: Berlin, Heidelberg, 2004; pp 81-92.

(11) (a) Chanthamath, S.; Nguyen, D. T.; Shibatomi, K.; Iwasa, S. Highly enantioselective synthesis of cyclopropylamine derivatives via Ru(II)-Pheox-catalyzed direct asymmetric cyclopropanation of vinyl-carbamates. *Org. Lett.* **2013**, *15*, 772–775. (b) Chanthamath, S.; Takaki, S.; Shibatomi, K.; Iwasa, S. Highly stereoselective cyclopropanation of  $\alpha_{\beta}$ -unsaturated carbonyl compounds with methyl (diazoacetoxy)acetate catalyzed by a chiral ruthenium(II) Complex. *Angew. Chem., Int. Ed.* **2013**, *52*, 5818–5821. (c) Chi, L. T. L.; Suharto, A.; Da, H. L.; Chanthamath, S.; Shibatomi, K.; Iwasa, S. Catalytic asymmetric intermolecular cyclopropanation of a ketone carbene precursor by a ruthenium(II)-Pheox complex. *Adv. Synth. Catal.* **2019**, *361*, 951–955.

(12) (a) Monnier, F.; Castillo, D.; Dérien, S.; Toupet, L.; Dixneuf, P. H. Addition of diazoalkanes to enynes promoted by a ruthenium catalyst: simple synthesis of alkenyl bicyclo[3.1.0]hexane derivatives. *Angew. Chem., Int. Ed.* **2003**, *42*, 5474–5477. (b) Monnier, F.;

Vovard-Le Bray, C.; Castillo, D.; Aubert, V.; Derien, S.; Dixneuf, P. H.; Toupet, L.; Ienco, A.; Mealli, C. Selective ruthenium-catalyzed transformations of enynes with diazoalkanes into alkenylbicyclo [3.1.0]hexanes. J. Am. Chem. Soc. 2007, 129, 6037–6049.

(13) (a) Trost, B. M.; Breder, A.; O'Keefe, B. M.; Rao, M.; Franz, A. W. Propargyl alcohols as  $\beta$ -oxocarbenoid precursors for the ruthenium-catalyzed cyclopropanation of unactivated olefins by redox isomerization. J. Am. Chem. Soc. 2011, 133, 4766–4769. (b) Trost, B. M.; Ryan, M. C.; Rao, M.; Markovic, T. Z. Construction of enantioenriched 3.1.0 bicycles via a ruthenium-catalyzed asymmetric redox bicycloisomerization Reaction. J. Am. Chem. Soc. 2014, 136, 17422–17425. (c) Trost, B. M.; Ryan, M. C.; Rao, M. Chiral cyclopentadienylruthenium sulfoxide catalysts for asymmetric redox bicycloisomerization. Beilstein J. Org. Chem. 2016, 12, 1136–1152.

(14) Wakatsuki, Y.; Yamazaki, H.; Kumegawa, N.; Satoh, T.; Satoh, J. Y. Regio- and stereocontrolled dimerization of tert-butylacetylene to (Z)-1,4-*di-tert*-butylbutatriene by ruthenium catalysis. Reaction mechanism involving alkynyl-vinylidene coupling and rearrangement of the metal-bound C4 unit. *J. Am. Chem. Soc.* **1991**, *113*, 9604–9610.

(15) (a) Katayama, H.; Ozawa, F. Convenient routes to vinylideneruthenium dichlorides with basic and bulky tertiary phosphine ligands (PPr<sup>i</sup><sub>3</sub> and PCy<sub>3</sub>). Organometallics 1998, 17, 5190-5196. (b) Oliván, M.; Clot, E.; Eisenstein, O.; Caulton, K. G. Hydride is not a spectator ligand in the formation of hydrido vinylidene from terminal alkyne and ruthenium and osmium hydrides: mechanistic differences. Organometallics 1998, 17, 3091-3100. (c) Bruneau, C.; Dixneuf, P. H. Metal Vinylidenes in Catalysis. Acc. Chem. Res. 1999, 32, 311-323. (d) Katayama, H.; Ozawa, F. Vinylideneruthenium complexes in catalysis. Coord. Chem. Rev. 2004, 248, 1703-1715. (e) Bruneau, C.; Dixneuf, P. H. Metal vinylidenes and allenylidenes in catalysis: Applications in anti-Markovnikov additions to terminal alkynes and alkene metathesis. Angew. Chem., Int. Ed. 2006, 45, 2176-2203. (f) Sung, H.-L.; Her, T.-M.; Su, W.-H.; Cheng, C.-P. Reactivity of ruthenium vinylidene complexes containing indenyl/dppe ligands and unsaturated bonds at cd with trimethylsilyl azide. Molecules 2012, 17, 8533-8553. (g) Smith, E. J.; Pridmore, N. E.; Whitwood, A. C.; Lynam, J. M. Synthesis of phosphonium-substituted vinylidene complexes from [HC=CCH<sub>2</sub>PPh<sub>3</sub>]<sup>+</sup>: exploring the competition between allene and vinylidene formation. Organometallics 2014, 33, 7260-7269.

(16) Yamaguchi, M.; Arikawa, Y.; Nishimura, Y.; Umakoshi, K.; Onishi, M. Vinylidene rutheniums with an electrostructurally-flexible NO ligand and their ruthenacyclobutene formation. *Chem. Commun.* **2009**, 2911–2913.